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TERRESTRIAL AND LUNAR FAULTS COMPARED

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When Galileo first looked at the moon through his telescope, he found that the large craters appeared to be like the sunken area of Bohemia rather than the ordinary type of volcanoes. This statement, repeated by Humbold in his *Cosmos*, is the clue to the understanding of the relationship of the moon to the earth in regard to geological structure. The most striking crater that would have produced this impression on Galileo's mind is Clavius, which is 142.6 miles in diameter and encloses 16,000 square miles of sunken surface (Fig. 1). Bohemia is an almost perfect replica, defined by a rim of mountain ranges: the Erz Gebirge on the northwest; the Sudetes on the northeast; the Bohemian Forest on the southwest; and the Moravian Heights on the southeast. From Eger to Grulich the depressed plain measures 120 miles.

To an African geologist the moon's surface appears familiar. There are the same bare rocks, the same faults; Europe and America are mostly covered with soil, while the predominating structure is folding not faulting. The writer has had the opportunity of studying the moon through a 9½-inch reflector, by Calver, a perfect instrument, and about the limit admissible for direct and prolonged observation under Grahamstown conditions; higher powers would produce fatigue and blindness. At higher altitudes, such as Johannes-

burg, an instrument of this power would have to be used with a screen, when all the finer details and the color effects would be lost. Fauth, who produced the most wonderful map of the moon, used a $6\frac{1}{2}$-inch refractor.

One notices, at the first observation of the "land" surface of the moon, two systems of cross-fractures, running northeast and northwest, with an occasional one north and south. In Africa the fractures follow the same directions (Fig. 2); slips of the earth's crust have been faulted down between parallel fractures forming the Red

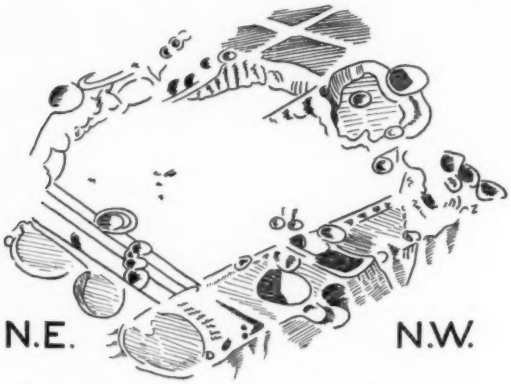


FIG. 1.—Maginus. Lunar fault pit, showing a fault plateau on the northwest and step faults on the northeast. Clavius is a similar pit.

Sea and the Gulf of Aden. From the angle between these, a southwesterly rift valley proceeds inland to Lake Rudolf, as the Hawash Valley, perfectly reproduced on the moon in the Alpine Cleft. From Lake Rudolf the valley divides into two—the western rift enclosing Albert and Edward Nyanzas, Kivu, and Tanganyika; while the eastern one is mostly dry land, with small lakes such as Naivasha, Manjara, and Baringo. These two rifts enclose Victoria Nyanza and join on the south at Lake Nyasa, whose rift continues down the Shiré River and through Portuguese East Africa. Here it meets the sunken rift valley, whose western edge cuts off the southeast corner of Africa in a straight line. The southern extremity of the continent is truncated by an east-and-west rift valley, the seaward side of

which comes up to the 100-fathom line. Inland there is an area from Port Elizabeth to the Cape traversed by shear-planes aligned paral-

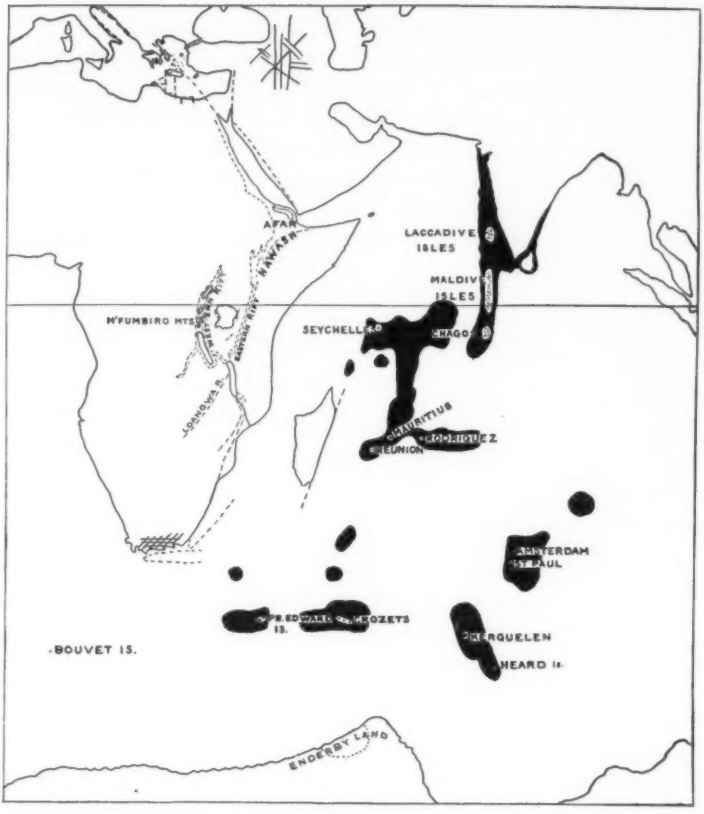


FIG. 2.—Map of Africa and the Indian Ocean, showing the fractures and submerged plateaus.

lel to the major faults, and between the crossing fractures there are the Baviaans' Kloof fault pits[1] and other patches of Cretaceous rocks

[1] E. H. L. Schwarz, *Report of the Geological Commission of the Colony of the Cape of Good Hope for 1903*, also *Causal Geology* (London, 1910) and *South African Geology* (2d ed., London, 1927).

let down into the Paleozoic rocks of the South Coast (Fig. 3). The basin of the Greater Ngami is of the same nature;[1] and the contours of the Swiss lakes strongly suggests that they too belong to the same category, and possibly the Great Lakes of North America as well. Structures on earth are obscured badly by the effects of weathering; whereas on the moon they are shown in crystal clearness, so that in many cases it is possible to obtain a solution of a terrestrial problem from evidence afforded by the moon.

A certain amount of atmosphere adheres to the moon's surface, and round the small spiracles there is evidence that gases are still being given off, for there appears to grow round them some kind of

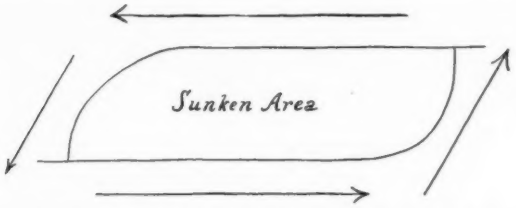


FIG. 3.—Diagram of one of the Baviaan's Kloof fault pits; Willowmore, Cape of Good Hope. The arrows show directions of thrust.

vegetation—lowly indeed, and perhaps to be compared with the fresh-water algae that grow upon the tiles of the roofs of houses, but which spreads as the season advances and in some cases dies out before the shadow of night reaches the particular spot. These plants would appear to derive their vital energy from the exhalations of the smaller volcanoes. The best area for observation is Webb's Mount Argaeus, between Mare Serenetatis and Mare Tranquilitatis. On the west are two small vents surrounded with circular fields of white ash. As the surface becomes warmed by the sun, a sooty growth appears on the landward side, which steadily advances till it surrounds the white patches. At the same time the black vegetation appears in all the valleys of the rocky promontory, up to the summits of the peaks.

A red color develops on the floor of Mare Serenetatis after the

[1] E. H. L. Schwarz, *The Northern Kalahari* (South African Geographical Society, Johannesburg, December, 1927).

first week of sunshine, which again is due, possibly, to a similar growth of red algae. It can be seen readily in most photographs of the "sea," and is noticeable because it does not reach the southern margin, leaving a bare black border some 10 miles broad on this side. The same red color appears in patches on the Mare Imbrium and less prominently in the eastern "seas," always where it may be surmised that exhalations are still issuing from small vents or where such gases might collect in the lower parts. Actual volcanic clouds in Schröter's Valley have been seen and drawn, while Linné supplies a case of a true volcanic eruption. Before 1866 Linné showed as a crater ring from 6 to 8 miles in diameter, but after that it disappeared in a smother of white ash; recently Fauth has drawn a small crater in the center, so that somewhere about 1866 there must have been an eruption after the style of that of Vesuvius in 79 A.D. The amount of weathering such an exiguous amount of gas could accomplish, aided by the puny efforts of a filmy growth of algae, would be negligible, even taking into account the passage of geological epochs.

The size of the craters varies from minute spiracles below the power of the highest magnification to resolve, up to giants more than 100 miles in diameter, and to the circular "seas" which are fundamentally the same in origin as the crater rings. Maginus offers a good example for explaining the nature of these structures. It is usually drawn as a circular basin; but in reality it is defined by four straight walls, which on the two northern sides are the boundaries of elevated plateaus. The fault plateau on the northwest, corresponding to the Riesen Gebirge in Bohemia, is particularly well shown; and a number of subsidiary vents have formed on the level top. The northeastern plateau, corresponding to the Sudetes, is occupied by three vast cauldrons of subsidence, 15–20 miles across, reminding one of the Ngorongoro Crater in Central Africa, alongside Lake Eyassie. On the interior there are three well-defined step faults, each with its own crater. The southeast wall is obscured by a huddle of lava flows; and between it and the northeast one there are cascades of solidified lava, rounding off what would have been a sharp angle. The southwest rim is pierced twice by walls of viscous, frothy lava, issuing from fissures that come down on to the floor of the de-

pression from the outer level surface; these fault lines are directed southwest-northeast. Owing to the small value of gravity on the moon, such exudations from gaping rents in the rocks would pile up to a considerable height before solidification; they are similar in nature to many sharp peaks scattered over the lava surfaces, which have been built up of this same kind of semiliquid rock issuing from a central chimney; hence no great stretch of imagination is necessary to enable one to ascribe the walls in Maginus to such a cause. The whole central area of the visible portion of the moon's surface is traversed by fissures running northeast and northwest, out of which has welled material evidently of this same frothy, viscous nature. Slag cones do exist in terrestrial volcanic areas, but here the weight of the mass causes them to spread out before rising very high; and nothing like the gigantic structures of the moon, such as the peaks known as Pico and Teneriffe, is possible. On the same southwest border there has developed a great cylinder of depression, with a terrace showing as a circular fault on the northern side; the southern interior shows just one bare fault face reaching from top to bottom. In the center, again, there is a small cylinder of depression. The angle between the southwest and northwest borders of Maginus is placed unfavorably for observation; one counts a great number of rounded crater rings, impinging on each other and grouped in series.

On the floor in the center of the main depression there are three minute cones, very difficult of observation; they only appear in moments of extraordinary pellucidity, and one has to wait many months before a favorable opportunity occurs. Their importance lies in the fact that they are aligned with the craters on the step faults on the northeast rim, showing that volcanic activity took place after the main depression had been blocked out.

The sequence of events shows that the crossing faults left a square segment of the moon's surface unsupported, so that it sank. The liquid below was invaded by the plunging mass, and lava became forced up along the fault-fissure bounding it; it welled over and filled up the depression to a certain height, covering the floor all over with a uniform sheet. In the structure called Birmingham there is a tunnel in the northeast rim down which any excess of lava would flow, repeating the conditions in Kilauea. After these operations

had been successfully carried to their completion, the sunken block broke across and small volcanic vents formed along them.

The last point was foreshadowed by Clough, Maufe, and Bailey in their paper on the Cauldron subsidence of Glencoe.[1] On the moon the best instance is in the great crater ring of Petavius, where the

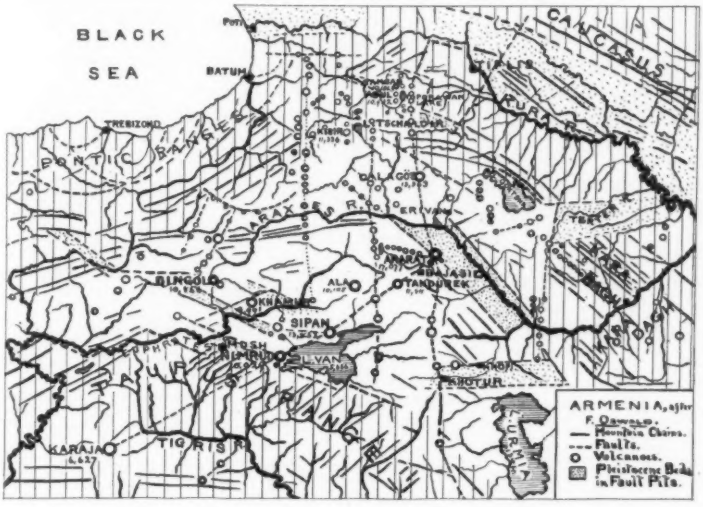


FIG. 4.—Map of Armenia, showing the similarity of the structure at the northern end of the Rift Valley system in Africa to that at the southern. Numbers of fault pits are shown, also fractures directed northeast and northwest, together with ones running north-south and east-west.

fault across the center of the cylinder is clearly shown. In other examples, the fault is obscured by the infilling of lava which covers the floor; but in the center of a very large number of crater rings there is a mound of viscous lava forming a hill, sometimes, as in Theophilus, with a tiny crater on top; this is due to the formation of volcanic chimneys along the fault, usually a single one, but in Maginus there are three. Tycho (Fig. 5) is an excellent example of a ring with the central mountain.

Elevated plateaus formed by parallel faults are of frequent oc-

[1] C. T. Clough, H. B. Maufe, and E. B. Bailey, "The Cauldron Subsidence of Glencoe," *Quarterly Journal of the Geological Society*, Vol. LXV (1909), p. 611.

currence all over the moon; the largest and most easily seen is that on the north of the Mare Crisium, but a more striking one is that between J. Hershel and Robinson. There is also a fine one north of Ptolemaeus, but it wants good side light to bring it up. In Birmingham the fault plateaus forming the rim are themselves faulted, so that they become converted into rift valleys. This amazing square structure, larger than Clavius, is badly shown, only appearing in its full beauty when the north pole is turned toward us in exceptional positions of libration; but as an example of a perfectly square fault-block it is without rival.

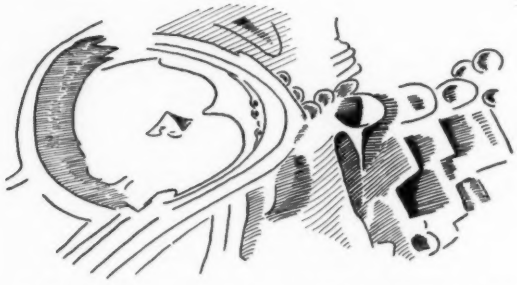


FIG. 5.—Tycho, showing a terrace with subsidiary volcanoes, and lava flowing over the floor of the depression; central mountain. Square pits on west, as on the south of Theophilus.

When the throw of the faults is strictly vertical, this quadrilateralism is the result; but if there is shearing, then the block inclosed in the four crossing faults is rolled and a cylinder is formed. Of the first case there are small examples, as in the square crater south of Theophilus (Fig. 6) or west of Tycho (Fig. 5). On earth these are represented by the Askja in Iceland, where a perfectly square block of basaltic tuff, 10 miles along each side, has been pushed up; the block has been cemented in position by lava issuing from the boundary faults. Then, when the liquid beneath was drawn off, the interior collapsed, as a joint of a telescope would, leaving an elevated rim surrounding the depression.[1]

[1] Hans Reck, *Island* (Stuttgart, 1912); Clough, Maufe, and Bailey, in the above mentioned memoir, give a wrong impression of this volcano.

In the second case, where a vertical cylinder is rolled out, we obtain the ordinary cauldron subsidence or crater ring (Fig. 7), first made known from the Ries and Hegau in Swabia.[1]

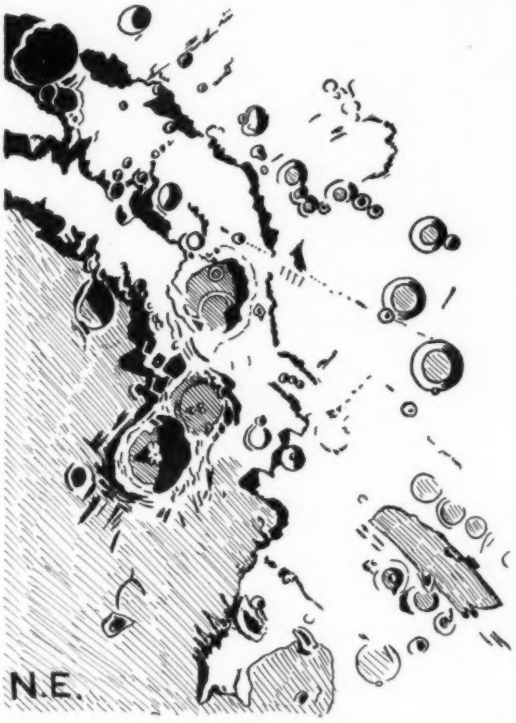


FIG. 6.—Mare Nectaris on the moon; southern margin. From Piccolomini the fault scarps of the Altai Mountains stretch northwest, meet a north-south fault, and continue in a northeasterly direction, ending in a bold headland overlooking the "sea." Theophilus and Cyrillus are two great crater rings between parallel faults; Catherina on the south lies to one side. Cyrillus has a concentric inner cylinder, Catherina an excentric one. Below the Altai Mountains are the two step-fault terraces. In the lower right-hand corner is a fault pit of the Baviaans' Kloof type, with three torsion cylinders on either side; one of these, Taylor, has developed a sunken pit, with central mountain; the rest are in embryonic stages. Theophilus is 64 miles across and 18,000 feet deep; the central mountain is 5,600 feet high and has a central crater.

[1] W. Branco, *Schwabens 125 Vulkan-Embryonen* (Stuttgart, 1894).

The transition from a square to a circular block is shown in the Baviaan's Kloof fault pits in the south of the Cape already referred to. The walls all round these are some 800 feet high, and they vary from 5 to 20 miles in length; the fault on one side curves round and meets the other at a right angle, the structure being reversed at either end. On the moon there is a precisely similar fault pit or crater valley, dominated by the volcano Taylor (Fig. 5). Here the walls are parallel, and run southeast; at the north end the southwest wall curves round, and at the south end the northeast wall curves round to meet the straight continuation of the opposite fault. Hypatia to the east is a boat-shaped crater formed by the apex of a similar structure; and Schiller, in the opposite quadrant, is of the same nature.

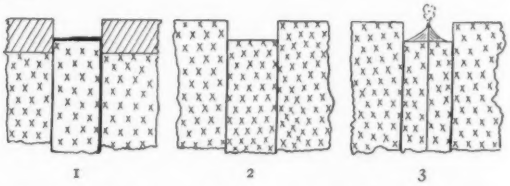


FIG. 7.—Torsion cylinders. 1, cylinder up: Ries, Hegau, in Swabia. 2, cylinder down: Glencoe. 3, cylinder down and fractured across: Steinheim, and lunar crater rings.

If the shearing is equal along all four sides, then a perfect vertical cylinder is produced. On the sides of the crater valley just described there are six such cylinders; on the northeast they are in various stages of development, becoming a full crater ring with central mound in Taylor, the others being in a less advanced state. On the other side, the cylinders are far less advanced in their development, the southernmost showing merely as a circular crack, such as might be made by a hammer head on soft wood. This is a case of a cylinder being blocked out by shearing, but no movement up or down has taken place; many observers have recorded these from all parts of the moon's surface.

The larger cylinders, Theophilus or Copernicus for instance, have had a very prolonged period of development, shown by the number of internal and external terraces, each marking an episode. The molten rock welled up the fissures, pouring over the newly formed

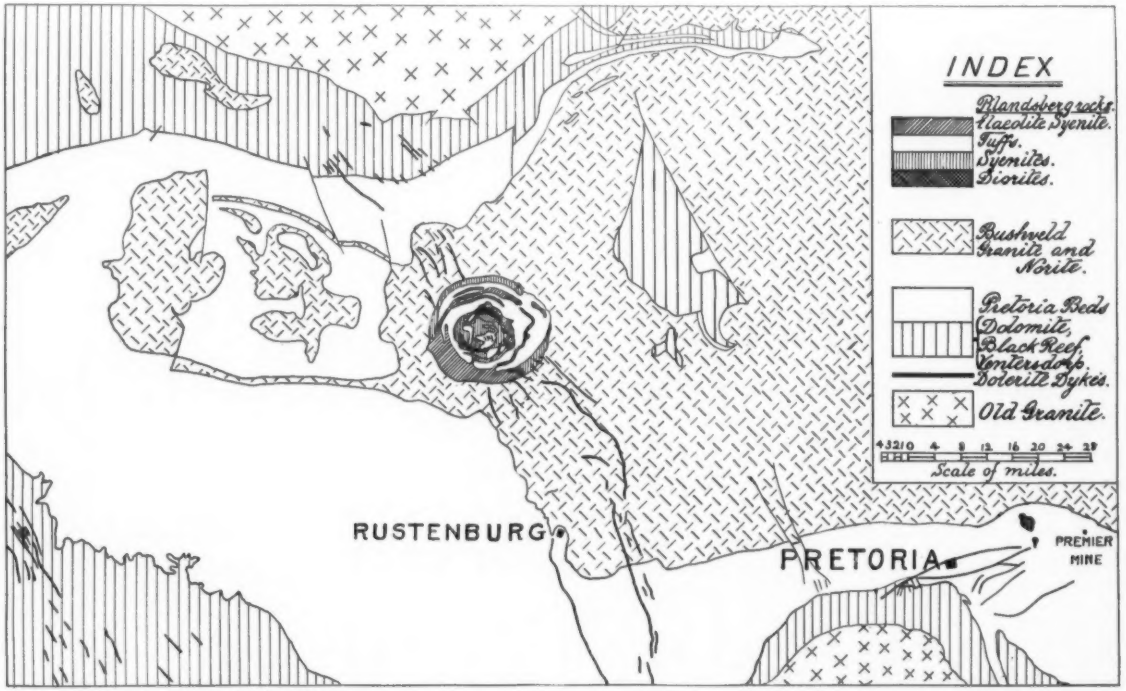


FIG. 8.—Map of Pilandsberg, Rustenburg district, Transvaal. A torsion cylinder showing concentric cylinders. Published by permission of the Minister for Mines, Pretoria.

fault scarp in cascades, which can be made out when visibility is good; often craterlets develop, as is the case in the Askja, which may remain as mere spiracles but which can and do develop into imposing volcanoes or independent cylinders of depression. The next paroxysm finds the elevated cylinder cemented in place; and contraction cracks have developed concentrically on the inside, so up goes the middle portion. The process is repeated till as many as six or eight outer terraces may be formed. Then follows a period of sinking, and the central cylinder drops in stages, becoming narrower and narrower at each and leaving behind terrace after terrace. Observers have described this terrace formation as "wreaths," and similar vague terms have been used; but a steady observation of Tycho, Copernicus, Theophilus, and especially Petavius, or indeed, any of the cylinders of depression, will convince one that they have been formed as described above.

To prove this further, nature has provided us with examples on a vastly greater scale in the *maria*, or lava seas. The best area to study in this connection is that on the south of the Mare Nectaris (Fig. 6). Here the Altai Mountains form the boundary, rising in an abrupt fault scarp; but below them are two wide terraces, 60 miles broad, falling by some 500 feet each to the floor of the depression. On them one sees all the subsidiary volcanic phenomena, which one can find, on a very much smaller scale, on the narrow terraces of the crater rings. The Altai Mountains further show how a straight fault is deflected into a curve, by a series of right-angled zigzags, a feature that is repeated on earth in the fault line along which the Cretaceous beds are dropped down against the Paleozoic rocks under the Zuurberg, near Port Elizabeth. The train of giant crater rings, Theophilus, Cyrillus, Catherina, show admirably how these cylinders are related to the major fault lines on the moon.

Most of the cylinders have sunk after full development, leaving a deep pit, out of which may peep the central cone rising above the outer rim. In one recorded instance, Wargentin, there has been only one period of collapse after elevation, consequently the lava welling up round the inner margin has breached the rim, which now only appears as a disjointed series of jagged crags. Between these the lava has found exit and has fallen with most picturesque cascades down

the outer fault face and onto the floor, over which it has flowed for considerable distances. The whole structure looks like a disc of cheese applied to the moon's surface. Another example occurs on the southern rim of Birmingham as observed at Grahamstown.

Clough, Maufe, and Bailey described Glencoe as a cylinder down, while the granite mass around Glen Etive is a cylinder up; the Ries is a cylinder up. Barnes, when describing the giant crater at Ngorongoro, obviously a cylinder down, stated that alongside was a vast circular elevated plain, devoid of trees, which is most probably the accompanying cylinder up.[1]

A parallel case to the Altai Mountains on the moon is that of the Apennines; but here the fault terraces are narrower, while the lowermost visible is sunk in the lava of the Mare Imbrium, only the tilted edges appearing. These mountains show a definite plum-color when seen toward the end of the lunation, contrasted strongly with the dead black of the lava floor of the sea. One is almost tempted to suggest as an explanation of the difference of tint that the mountain rocks are nepheline basalts while the lavas of the *maria* are ordinary olivine ones. The lunar Apennines recall the Abyssinian fault scarp overlooking the Red Sea.

The general elevation of the northern half of the moon, where most of the lava seas occur, is less than that of the southern half, which constitutes most of the "dry" land. The whole surface in the latter is crisscrossed by fault lines, mostly northeast and northwest; but every now and again there is a meridional one. The crater rings are strung out in trains following these, but the faults are themselves the seat of extrusion of viscous lava which makes their presence noticeable, and also of definite crater rows, as in Laki in Iceland.

The lava of the seas covers everything, as do the Columbia River lavas; and it is a fair inference that the surface thus hidden is likewise riven by crossing faults, from the gaping orifices of which the molten rock issued. In the north, owing to the lower elevation, the material which gushed out was liquid lava; but in the southern area, because of the greater elevation, only the frothy scum was extruded.

[1] T. A. Barnes, "The Highlands of the Giant Craters," *Geographical Journal* (London), 1921, p. 401.

This origin for the lava fields of the moon is borne out by what is found in Scotland. The Tertiary lava field extended all over the British Isles, from the Menai Straits to Greenland, a distance of 2,000 miles or more. Iceland as a whole is a cylinder up, gouged out of the volcanic rocks by the same processes that produced the crater rings. Except for small areas round Antrim, in the north of Ireland, and in the Inner Hebrides, this covering of lava has been removed by denudation, yet the supply-dykes occur as thickly and are orientated in the same direction as one may observe in the central parts of the moon; an inspection of the detailed maps of the Scottish Geological Survey, especially of some areas on the west, will convince one of the identity of the terrestrial and lunar phenomena. South Africa was once similarly covered, but the Drakensberg lavas that extend from near Port Elizabeth to the Victoria Falls, and from Natal to the west coast, are Jurassic.

The crater rings show the fault scarps so extraordinarily clearly that they cannot be geologically old. Admitted that there is no atmospheric weathering on the moon, yet there is intense expansion and contraction due to the alternate periods of exposure to the sun's rays and to the cold of outer space. If one studies carefully any of the great fault scarps—such as that in the Sinus Iridium, 15,000 feet high, and admirably situated for observation—one sees no sign of crumbling, nor are there any accumulations of screes at the base. In the Straight Wall, there has been no fall of rock, and the fault face is as sharp as when it was first developed.

This leads to the conclusion that the later features on the moon are not older than Tertiary, with the necessary corollary that they are contemporaneous with the same phenomena on earth—production of lava fields over vast areas, faulting in the Indian Ocean and the continent of Africa, but of course, not folding. If the capture theory of the moon is correct, then our satellite would have come within the attraction of the earth at the beginning of the Tertiary period, and the sudden arrest of revolution by both planetary bodies would have given rise to all the phenomena observed. Shearing in two directions, northeast and northwest, with occasional meridional and east-and-west fractures would follow from such a sudden check. Even if one only takes into consideration the manifestations on

earth, it is difficult to adduce any adequate force that would cause the earth's crust to give way to a torque unless we bring in an outside body; and when we perceive exactly the same on the moon, it is legitimate to argue that the outside body was the moon.

Pickering, observing at Arequipa in a moment of perfect visibility, saw the cliff wall of the Sinus Iridium composed of giant conglomerate, in which the huge bolides were massed together with cavernous spaces between. At Grahamstown the same thing was seen in the cliff forming the crater ring of Hommel, in the opposite quadrant.[1] As the definition of the instrument here is limited to objects ½ mile in diameter, the blocks in the wall of Hommel must have been about 800 yards across. These two instances are sectional views of the actual substance of the moon's outer surface.

Owing to the development of water on the earth, all the surface rocks have been weathered throughout geological time; the iron content is leached out and washed down by the rivers but rarely reaches the sea—it passes downward, sometimes to enrich the rocks in its course, forming deposits of iron ore, but elsewhere disappearing altogether. Going back in the earth's history, all that iron would be in place at the surface, making the composition of the original crust an ultra-basic rock. If this argument is correct, then the moon represents our earth in its early stages, before water came to be formed by the decomposition of the meteoric gases, CH_4 and CO_2.

In Africa we have the large fault pits of the great lakes, most of them conforming to the Baviaan's Kloof type—that is, they are elongated—but Victoria Nyanza is a circular depression bounded by faults. Lake Tsana in Abyssinia is a square fault-block subsidence, the marginal fissures having given exit to lavas that have piled themselves into vast mountains. In Southwest Africa, there is the square granite block of the Erongo Mountains, with a sunken area in the center, like that in the Askja; the Ahaggar, in the western Sahara, is the same, with a volcano issuing from the south inner margin. In Asia two enormous square fault blocks occur in the Ordos, around which the Hoang Ho River makes a right-angled turn; and in Angaraland in the north.

Giant craters of the lunar type occur all over Africa. The north-

[1] *Nature*, September 4, 1926.

ernmost is Emi Kussi, to the east of Lake Chad; the better-known ones are those to the north of Lake Eyassie, southeast of Victoria Nyanza. Geitsi Gubib is one of these enormous crater rings in Southwest Africa; and in the Transvaal there are at least three. Pilandsberg is interesting from the fact that there are several concentric cylinders, from the fissures separating each of which there have issued various types of felspathoid lavas; then, north of Pretoria, there is a perfect "cylinder down" in the Salt Pan on Haman's Kraal, the pit being rimmed by a concentric fault forming a terrace. Finally, the Vredefort Mountain land on the Vaal River is a cylinder up," thrust into Witwatersrand beds, with most interesting phenomena of frictional heat on the margins. The last example is a close parallel to the Ries, or to the lunar structure called Wargentin.

To sum up the above mentioned facts, we have in Africa a continent that was fractured while the others were subjected to folding at the commencement of the Tertiary period. In spite of a great deal of weathering, many of the effects are still apparent—the walls of the Rift Valley, for instance, standing out as sharply as the corresponding feature on the moon, the Alpine Cleft, or the rift valleys west of Birmingham. From elongated fault troughs one passes into eye-shaped fault pits of the Baviaans' Kloof type and from them to the giant craters, so that all of them are related in origin. All of them may consist of single faults; or they may be stepped, giving terraces. Every phase of such structures on the earth can be matched by examples on the moon, so that our satellite affords subjects for study that cannot fail to help us with our own geological problems. Although this paper is confined to African occurrences, which have been the life-study of the writer, nevertheless there are extensive tracts of faulted rocks, in Asia and in the Rocky Mountain region for example; and the moon may be expected to shed light on obscure points in the tectonics of these areas as well.

THE GEOLOGY OF ANCON POINT, ECUADOR, SOUTH AMERICA

GEORGE SHEPPARD

ABSTRACT

A type area of Tertiary sedimentation is described which occurs to the south of the Santa Elena peninsula. Though the discussion is confined to one area, the observations can be applied in general to the Tertiary formations which are found along this part of the coast belt. An attempt is made in the stratigraphical succession to zone certain of the Oligocene and Eocene formations, and a description is included of the lithological types which occur in the series. The presence of igneous dikes and the incorporation of "foreign" volcanic rocks in the Tertiary sedimentation is also discussed, and a general account given of the geological history of the formations. Brief reference is also made to the Quaternary deposits, which occur in the form of raised "terraces," and are locally known as *tablazos*. Ancon Point itself is a structural outlier of Oligocene beds faulted against the Eocene formations of the mainland. In addition to a description of the local features of structural interest, a general review of the regional tectonics is included.

INTRODUCTION

The area to be described is situated about twelve miles to the southeast of La Puntilla, a prominent landmark which forms the most westerly extension of the mainland of Ecuador. The prominence of Ancon Point at the present time has been determined largely by the hard and resistant nature of its geological formations, as both to the immediate northwest and southeast, respectively, the rocks consist of soft shales and sandstones. The point itself is made up principally of hard, compact, and massive sandstones with intercalated conglomerates.

The topography of Ancon Point is rugged, and the surface is deeply incised and dissected by short, truncated river courses which invariably terminate at the coast in the form of hanging valleys. The latter are undoubtedly remnants of longer drainage channels which existed prior to the recession of the coast line. The major fault, which can be seen below the petroleum settlement known as Ancon (Fig. 2), was probably responsible, in the first place, for the actual formation of Ancon Bay. To the east of the fault, the strata include soft shales and sandstones (Eocene) which are faulted up against the

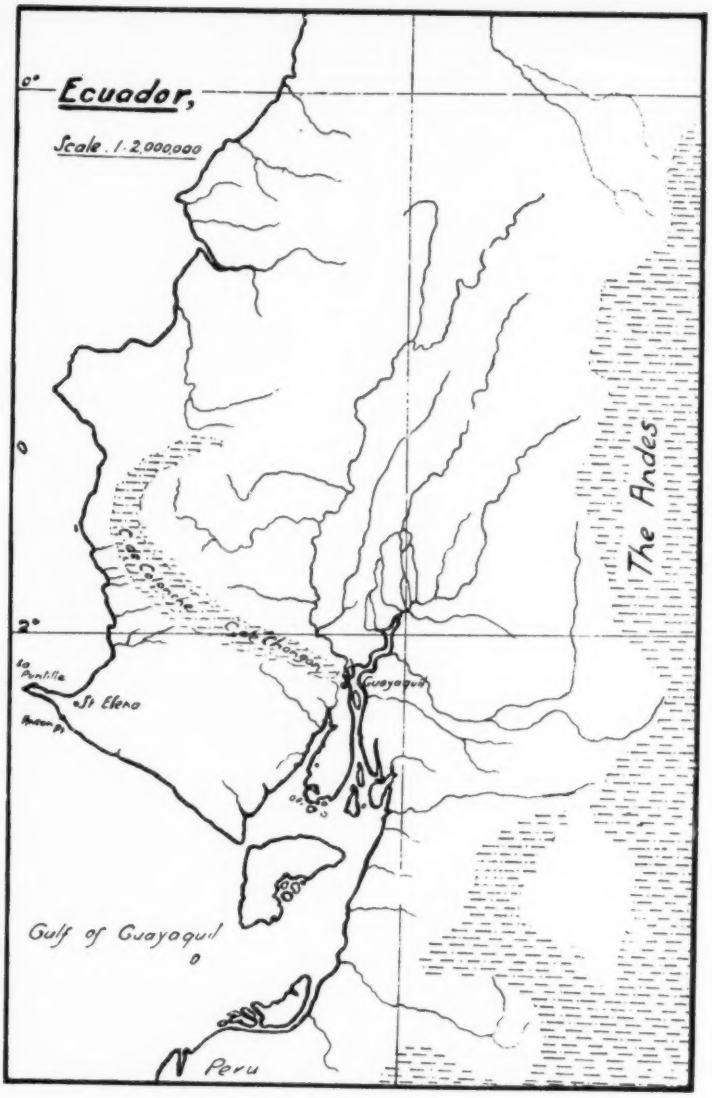

Ecuador,
Scale. 1.2,000,000
0°
2°
The Andes
Guayaquil
St. Elena
Gulf of Guayaquil
Peru

FIG. 1

harder formations of the Oligocene. It is of interest to observe that this major fault, with its subsidiary ramifications, continues through the headland itself, and it is quite possible that in the course of time

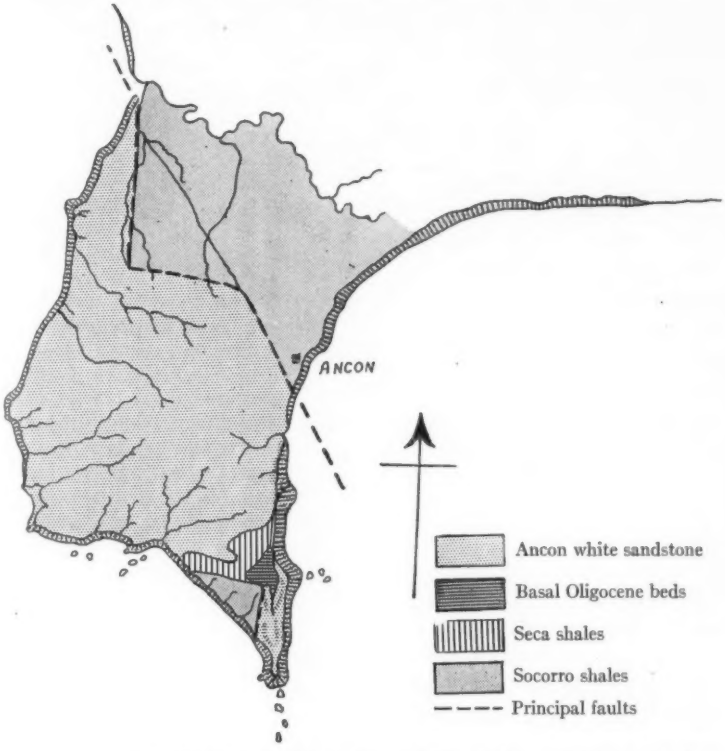


FIG. 2.—Geological Map of Ancon Point, Ecuador. Scale: 1:25,000, or 2.5 inches to 1 mile. Recent and Quaternary deposits not shown.

the point will be separated from the mainland along the plane of dislocation. The highest part of this area has an elevation of about two hundred feet above sea-level, the Tertiary formations being capped by remnants of a raised beach, or terrace, of Quaternary age.

In contrast with their homotaxial equivalents in Peru, the Ter-

tiary strata found along the coast belt of Ecuador are peculiarly devoid of organic remains, and, with the exception of certain Foraminifera,[1] local lenses of gastropods, occasional indeterminate fragments of mollusks and fossil wood, etc., a study of the fauna in these Tertiary beds does not contribute much to the problem of subdividing the various stages which are found in the sedimentation. Certain lithological phases do persist, however; they have a definite strati-

THE STRATIGRAPHICAL SUCCESSION

TABLE OF FORMATIONS

			Feet
QUATERNARY	Pleistocene	Raised sea beaches (*tablazos*)	20– 50)
	Unconformity		
TERTIARY	Lower Oligocene	Ancon Point stage	
		(1) Ancon white sandstone	(30– 40)
		(2) Variegated shales and sandstones	(100)
		(3) Massive sandstone (ball type)	(50)
		(4) Laminated shales and sandstones	(35)
		(5) Tabular sandstones (gastropod zone)	(50)
		(6) Basal breccia	(35)
	Unconformity		
	Upper Eocene	Seca shales stage	(30– 300)
		Disconformity	
		Socorro stage	(800–1,000)

graphical sequence, and hence can be correlated in the field with a reasonable amount of accuracy.

The nature of the continental mass from which the Tertiaries were denuded is, as yet, imperfectly known, but the fact must not be overlooked that certain later Tertiary deposits may have been formed themselves from the direct denudation of an earlier Tertiary land surface. In pre-Tertiary times the coast line in Ecuador was formed to a large extent of Cretaceous limestones, with which were associated large intrusions of syenitic rock and allied petrological forms. As the foregoing represent, even at the present time, the extreme westerly ranges of the huge complex known as the Andes, it must be assumed that the deposits now recognized as being of undoubted Tertiary age had their origin in the denudation and redistri-

[1] T. Wayland Vaughan, "Foraminifera from the Upper Eocene Deposits of the Coast of Ecuador," *Proc. Nat. Acad. Sci.*, Vol. XII, No. 8 (August, 1926).

bution of the material derived from this Cretaceous, or possibly earlier, continental landmass. It is only by a close investigation of the mineralogical and lithological constituents of the present Tertiary sandstones, shales, and conglomerates, and their comparison with the Cretaceous and older rocks of the interior, that a definite conclusion can be put forward regarding the origin of the Tertiary formations. These, in Ecuador, attain great thicknesses, and present many features of depositional interest.

TERTIARY

A subdivision of the Tertiary formations found in this area has been made possible by faunal investigations and a study of the lithological characteristics of the respective strata. Organic remains are not common in the Tertiary deposits of Ecuador, with the exception of the Miocene, but sufficient evidence of true diagnostic value has been obtained to indicate that the lower sandstones and shales are of Upper Eocene age.[1] In upward succession from this known horizon, the Oligocene age of the upper beds has been determined more or less upon lithological and stratigraphical grounds. The following fossils have been collected from the Socorro stage of the Eocene (by Mr. A. J. R. Murray and the writer) and subsequently identified by Mr. H. H. Olsson.[2]

Phacoides subpennsylvanicus n. sp.
Amusium (*Propeamusium*) *aturicum* n. sp.
Turritella
Arca sp.
Nummulites
Operculina
Lepidocyclina

According to Olsson the *Phacoides subpennsylvanicus*, the *Nummulites*, and the *Operculina* show quite conclusively that the Socorro stage must belong to the Upper Eocene, this being part of the Lower Lobitos formation (of Bosworth)[3] in Peru.

The Socorro stage of the Eocene is succeeded by a thickness of compact shales, known as the Seca shales, which are light gray in color upon their weathered surfaces. This coloration is due undoubtedly to a capillary exflorescence of calcium carbonate caused by the action of tropical weathering.

[1] T. Wayland Vaughan, *ibid.*, p. 3.

[2] Personal communication.

[3] *Op. cit.*, p. 22.

GENERAL LITHOLOGY OF THE SEDIMENTS

UPPER EOCENE

Socorro stage.—Although the Socorro occurs only in the Ancon Point area forming fault blocks associated with the Oligocene strata, and is never found as a normal sequence, it is considered relevant to give some brief description of the deposit.

To the east of the area, the Socorro stage, which includes sandstones and shales, is well developed regionally and outcrops both along the coast and inland over a considerable territory. This stage consists principally of soft shales with intercalated thin sandstones (Fig. 3), but only near the top of the sequence does a sandstone horizon attain any great thickness (12–20 ft.). The shales are of the normal Tertiary variety, known as *gredas* in Peru, and vary in color from light slate-gray to black.

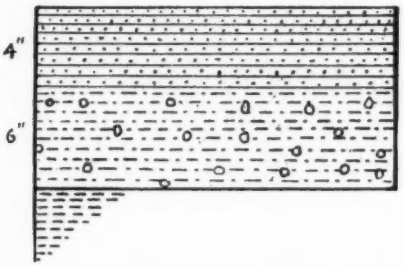


FIG. 3.—Section in Socorro shales (Eocene), cliff below Ancon settlement. 4" thin-bedded, fine- to medium-grained sandstone, contains Foraminifera (Orbitoids). 6" rubbly brown clay, sandy, rolled and angular quartzite pebbles, almost a "grit."

The separation of iron compounds, chiefly of a concretionary nature, is caused by weathering upon the exposed surfaces. The superficial shales are also rich in gypseous segregations, the latter occurring both as small groupings of fine, acicular crystals and as thin veins.

The sandstones vary appreciably in hardness and in texture; they are usually ferruginous, and a mineralogical investigation of their constituents has revealed quartz, quartzite, felspars (albite and anorthite), micas, calcite, tourmaline, and magnetite. Although there is no direct evidence for the observation, it is possible that both the sandstones and shales of the Socorro stage have been derived from the denudation of some granitic outcrop, probably one of the western ranges of the Andes.

In addition to the gypsum deposits found in the shales, cone-in-cone structure is well developed in certain horizons, notably in as-

sociation with concretionary structures. Fossils are by no means common in the Socorro shales, but the following have been collected, and subsequently named, by the authorities quoted:[1]

Foraminifera:
Orthophragmina sp.
Lepidocyclina sp.
Nummulites sp.
Operculina sp.
Cristellaria rotulata

Pelecypoda:
Ostrea sp. *Callista* sp. *Lucina* sp. *Cyathodonta* sp.
Amusium sp. *Cardium* sp. *Pecten* sp. *Venericardia* sp.

Gastropoda:
Phos sp. *Bittium* sp. *Pleurotoma* sp. *Turritella* sp.
Liotia circulis. *Oliva* sp. *Crepidula* sp. *Crucibulum* sp.

Scaphopoda:
Dentalium sp.

Cephalopoda:
Nautilus sp.

Vertebrata:
Teeth of Lamma and other fish, with scales

Seca shales stage.—The Seca shales, found along the coast sections and inland to the east of Ancon village, are of Upper Eocene age, and are superimposed unconformably by the Lower Oligocene. The shales are of limited distribution, and although in other parts of the same region the formation has a thickness of about three hundred feet, it thins out considerably near Ancon Point, being represented by approximately thirty feet. The shales are remarkably uniform lithologically and consist of gray homogeneous material, for the most part unfossiliferous, with the exception of radiolaria and small serpula-like calcareous tubes. Exceptionally large pseudo-concretions up to twenty or thirty feet in length occur in certain horizons, and, while these have interesting features of structural importance, their exact mode of origin has yet to be determined. Unlike most concretionary forms they are non-nuclear, the bedding planes of the country rock pass through the "concretion" without interruption, and the cracks or minor joints in the structure are filled with a

[1] The Foraminifera have been named by Dr. Wayland Vaughan, other fossils by Mr. H. H. Olsson (personal communication).

curious mammillated form of silica (probably opal). Small iron oxide concretions also occur throughout, these being usually tabular or lenticular in habit.

Weathered sections of the Seca shales vary from light gray to white in color. This, however, is purely superficial and does not penetrate very deeply into the rock. The light color and softer texture of the shale has been induced, no doubt, by the action of tropical climatic conditions, where the rapid evaporation of solutions, brought to the surface of the rock by capillarity, has caused the deposition of calcareous and other salts.

The disintegration of shale formations, with consequent denudation, is especially rapid under the conditions which obtain in this part of Ecuador. Long, relatively dry seasons, alternated by short periods of heavy rainfall, have a great destructive effect upon all exposed rock surfaces. Constant desiccation in the solar heat for at least nine months of the year renders the superficial strata peculiarly susceptible to rapid disintegration by water, and it has been noted that after a heavy shower of rain a fragment of Seca shale will be resolved from the solid rock to a flocculent mass of amorphous clay within twenty-four hours.[1]

LOWER OLIGOCENE

Ancon Point stage.—The Ancon Point stage of the Lower Oligocene forms the greater part of the headland under discussion. This stage has been divided into six lithological units for the purposes of correlation (p. 6), and as these differ so much both in appearance and constitution, it has been considered necessary to describe each phase in detail.

The whole sequence is normal in a depositional sense, and although pronounced variations undoubtedly occur in the respective subdivisions, no evidence whatever of unconformity or even lateral variation has been observed in the continuity of these sections. There is a possibility, however, that the sandstone members of the series are distinctly lenticular in habit, as carefully measured sections of the same stratum have revealed differences in thickness over comparatively short distances. As will be discussed later, the conditions

[1] G. Sheppard, "The Occurrence of Gypsum in the Tertiary Sandstones and Shales of Ecuador," *Geol. Mag.*, Vol. LXIV, No. 757 (1927).

which originally governed the deposition of these sediments were such that relative uniformity in the development of the respective strata would be almost impossible.

The total thickness of the Lower Oligocene beds in this area does not exceed five hundred feet, though it is obvious that an enormous amount of the pre-Quaternary land surface, i.e., consisting of Tertiary formations, had been removed by denudation prior to the deposition of the *tablazos*, as the Quaternary formations are called.

1. *Ancon white sandstone.*—The Ancon white sandstone forms the highest observed stratigraphical unit of the Lower Oligocene, and it can be easily recognized by its striking light color, by the habit of its weathering, and by the nature of its lithology. The formation rarely exceeds a thickness of forty feet, and it conformably overlies a series of buff, or brown, tabular sandstones with interlaminated shales. The white sandstone is normally soft and friable, and disintegrates rapidly upon exposure. It is interesting to note, also, that this same sandstone, in cases where it has been subjected to tectonic stress, has been reduced locally to the state of a rock powder, whereas the contiguous country formations have been relatively unaffected.

The sandstone varies in texture from fine to coarse grain, and in places it passes into a breccia of white, opaque fragments. The rock is essentially non-calcareous, and many of the included fragments have been recognized under the microscope as decomposed volcanic ash. It has been determined further that a high percentage of the rock itself consists of actual volcanic glass of a pumice type, the opaque white fragments also including small crystals of biotite.

The Ancon white sandstone is occasionally laminated, and although the rock is made up largely of detrital volcanic material, it is curious to observe that the actual bedding planes include, not infrequently, thin partings composed entirely of brownish fragments of vegetal origin, such as fossil leaves and siliceous wood fibers. In many instances, the sandstone passes into a true volcanic tuff, and this has probably been accumulated from the weathered débris of a lava flow. The fresh and angular appearance of the included fragments, also, indicates that the material has not been transported from any great distance. The sedimentary phase under discussion weathers in a peculiar, yet characteristic, fashion, and disintegrates very rapidly

as compared with other rocks of the same series. The respective strata are jointed and split up by fracture planes, the whole outcrop appearing to be divided into groups of closely assembled cubes few of which exceed six inches or so in dimension. The effect of continuous weathering, however, is to round off the corners of these blocks, with the result that a "cobblestone" appearance is produced which, in itself, is quite diagnostic for the formation.

2. *Variegated sandstones and shales.*—Although a defined line of demarcation is always found between the Ancon white sandstone and

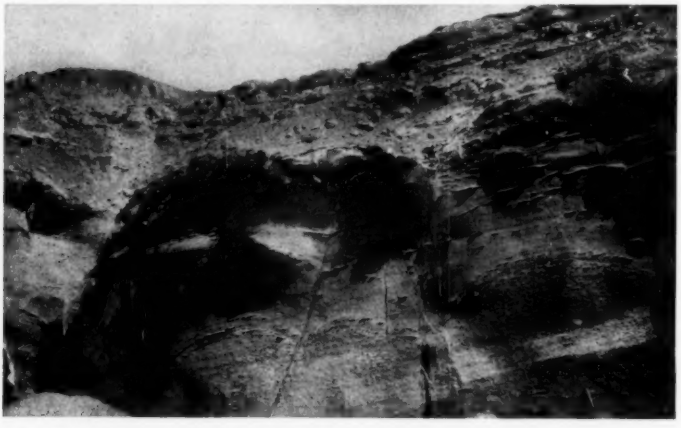


FIG. 4.—Exflorescences of selenite on exposed Oligocene sandstones, Ancon Point

the underlying variegated sandstones and shales, there appears to be no evidence of a stratigraphical hiatus. The two subdivisions, however, are quite distinct lithologically, and the sandstones of the variegated series consist of angular, or rounded, quartz grains cemented in a ferruginous base. Tabular bands of massive, coarse-grained sandstone form the upper part of this subdivision, and current bedding is a common feature.

The sandstone horizons are interbedded by thin shale bands toward the base, and these invariably have a dark-brown color due to the presence of fossil-plant fragments. The latter, however, are so macerated that it has been impossible to collect specimens suitable

for identification purposes. In common with other sandstones of the Oligocene, secondary gypsum has been formed in considerable quantity upon the exposed surfaces, and usually occupies fault or joint planes. Plates of this mineral are a characteristic feature of the coastal cliffs, and as these plates are more resistant to weathering than the sandstone itself, they stand out as solid veins in conspicuous relief (Fig. 4).

3. *Massive sandstones (ball type).*—Next to the Ancon white sandstone the foregoing deposit is the most easily recognized horizon

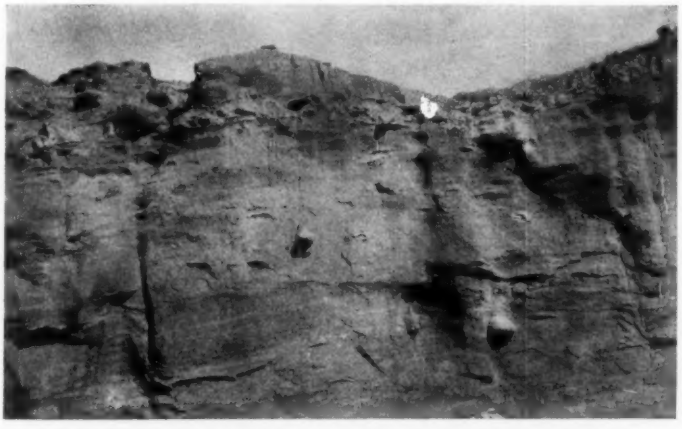


FIG. 5.—Oligocene sandstone showing "ball" structure, near Ancon settlement

of this stage of the Oligocene, and consists essentially of massive, well-bedded sandstones, with occasional partings of thin shale. The sandstone is medium to coarse grained in texture, and frequently passes laterally into a local grit or fine conglomerate.

The most important feature of the deposit, however, is the presence of large "balls," or spheroidal masses of sandstone, which range in diameter from six inches to four feet (Figs. 5 and 6). Although there is reason to believe that the spheroids are secondary to the original stratification, no suggestion whatever either of lamination or bedding has been noticed in the spheroid itself. The center is usually very hard and compact, being often so coarse grained as to

approach an angular grit. The sandstone itself is calcareous, and apparently the individual quartz grains are inclosed ophitically in the calcite of the groundmass.

FIG. 6.—Oligocene sandstone showing "ball" structure, near Ancon settlement

In addition to the quartz element, white mica, greenish indurated shale, and black quartzite have been observed as constituent ingredients of the sandstone. The spheroidal masses are also rarely

fine grained in texture, and exhibit a conchoidal fracture due to the calcification. Of considerable importance is the fact that the large spheres exfoliate upon exposure to the atmosphere, and the resulting decomposed material flakes off in a concentric manner with a separation of various iron compounds. The spheroids are typically non-nuclear, the freshly broken matrix being homogeneous throughout. It is impossible at the moment to state with certainty the reason for the actual growth or development of these curious structures in the sandstone. The process may be entirely one of chemical action, being due, in all probability, to a primary separation of calcite from the constituents of the parent-rock. During this phase of calcitic aggregation all traces of the original stratification became obliterated, and the later crystallization caused the matrix of the spheroid to assume a homogeneous nature.

The phenomenon of exfoliation is one of the first effects of tropical weathering upon certain exposed rock surfaces, more especially in connection with the combined action of strong chemical solutions with high temperatures. It must be remembered, also, that the rainfall in this part of Ecuador is limited to one or two months of the year, though in addition heavy mists are prevalent which have the effect of materially assisting in the denudation of the exposed outcrops. The intense heat of the sun in these latitudes causes capillary water to be withdrawn from the outer layers of the rock on an extensive scale, which process brings the soluble salts or sodium, magnesium, etc., to the surface, thus causing a degradation of the upper layers of the formation.

In the case of the spheroidal sandstones it can be readily appreciated that the effect of capillarity is confined to the outer shell of the spheroid (probably not more than an inch in depth), and when this layer disintegrates a new surface is formed which, in its turn, is subjected to the same chemical processes induced by the capillary water. As a general rule, the decomposed shells of sandstone flake off concentrically, and they have been observed to contain crystalline selenite with varieties of iron oxide such as limonite and red ochre. These minerals are obviously of secondary origin, having been produced by the chemical action referred to above. In this case it is questionable whether variations of temperature have any influence

upon the process of exfoliation, the phenomenon more probably being due entirely to the chemical changes induced by the circumstances of tropical weathering.

4. *Laminated shales and sandstones.*—This areno-argillaceous series has a development of thirty-five to fifty feet and follows normally below the massive sandstone horizon described above. Unlike the majority of the similar formations found in the Oligocene, the laminated beds are characterized by a chocolate-brown color, this being due, in part, to the presence of finely disseminated plant remains with brown lignite in a fragmental condition. The respective alternations of shale and sandstone are finely stratified and frequently veined by plates of gypsum. On the whole, the deposits are loosely consolidated, the sandstone elements grading from medium to coarse grain. Toward the base of this subdivision the formations become uniformly more arenaceous, and the laminated nature of the sediments is replaced by marked current bedding. The lower sandstone horizon in which the latter feature is exhibited forms the base of this series, below which the tabular sandstones are found.

5. *Tabular sandstones.*—The tabular sandstones attain a thickness of fifty to seventy feet and are distinctive by reason of their uniform coarseness of texture, by the number of included rock fragments, and by the presence of certain organic remains. The deposits are tabular in habit on the whole, and vary lithologically from extremely coarse-grained sandstones to lenticular seams of true conglomerate. In addition to the normal constituents of such a sandstone, rounded fragments of fossil wood occur in profusion. The rolled appearance of the latter indicates either that they accumulated on a tidal beach or that they were transported, probably by river action, from some distant source. White and buff-colored siliceous wood is also found in association with the carbonized fragments.

The presence of large quantities of included volcanic rocks, the majority waterworn, comprising compact black vesicular basalt or andesite, and lava of a pumice type, is not without significance. Imperfect fragments of carbonized plant remains and certain fossil fruits have been collected also from this horizon.

As a general rule, the tabular beds of this subdivision are jointed

at high angles to the bedding, and faults of considerable throw are not uncommon. These fissures have been later filled in by quartzo-calcitic veins, some of which measure several inches in thickness. It is of interest from a mineralogical point of view to note that an opaque form of yellow calcite forms the outer wall of the vein while the center always consists of crystalline quartz.

Toward the base of the section an irregular calcareous mudstone (almost a limestone) is found which has a maximum thickness of about ten feet. This was originally a fine-grained mud or silt, and it now forms a distinct and reliable horizon in the normal succession. The calcareous zone is also crowded with gastropods of the form *Hemisinus;* the latter, however, has not yet been determined specifically. The gastropod zone can be readily identified throughout the whole of the area dealt with in this paper, as the screes formed from the denudation of the stratum are full of these fossils and the horizon can be mapped with little difficulty along the coast sections.

Reverting to the quartzo-calcitic veins described above, it is noteworthy that the fossil gastropods have a similar mineralogical habit. The shell and outer whorls of the organism consist entirely of calcite, while the internal casts are siliceous in character.

The underlying beds of this subdivision are very irregular and lenticular below the gastropod zone, a condition which persists until the true basal breccia is reached.

6. *Basal breccia.*—The basal breccia is a heterogeneous sandstone formation, of varying thickness, probably averaging about thirty-five feet. It is similar in many respects to certain of the more conglomeratic horizons found higher in the succession, but the included igneous types are rare. On the other hand, the majority of the foreign blocks found in the breccia consist of angular sandstones as well as exceptionally large masses of altered shale. The latter are considered to belong to the Seca shales stage of the Upper Eocene, and the preponderance of these boulders in the basal breccia indicates that they probably represent a definite surface of erosion. Wherever observed, the breccia rests unconformably upon the underlying deposits, the surface of which was eroded considerably prior to their superposition by the sandstones and shales of the Oligocene.

Many of the decomposed shale blocks are of large size, but it is

evident, both from their state of preservation and from their attitude in the breccia, that they have not been transported from a locality very far distant. The shale inclusions undoubtedly represent talus or beach detritus which has become later incorporated into a sandstone facies. The fact that many of the shale "boulders" have been perforated by marine boring mollusks before their consolidation in the breccia is of considerable interest. The altered or decomposed nature of the shale blocks is well exemplified by the manner in which they

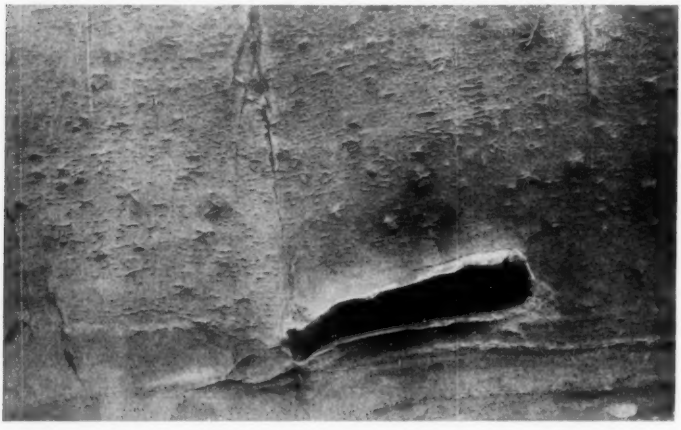


FIG. 7.—Cavity in Oligocene sandstone caused by removal of included shale block by marine erosion, Ancon Point.

are readily disintegrated at the present time by the usual atmospheric agencies.

Large cavities in the breccia are conspicuous in the cliffs of the coast, these representing the shale blocks which were later disintegrated by local wave action (Figs. 7 and 8).

Considerable quantities of fossil wood and white quartzite pebbles are common in addition to the constituent members of the basal breccia described above (Figs. 9, 10, 11).

QUATERNARY

The Quaternary deposits found in this area can be referred to the Pleistocene, and consist in the main of raised sea-floors which are

known as *tablazos*, or "tablelands." These sediments include shell limestones, calcareous sandstones, lenticular shales, and loosely consolidated detrital beach material, being always found resting uncon-

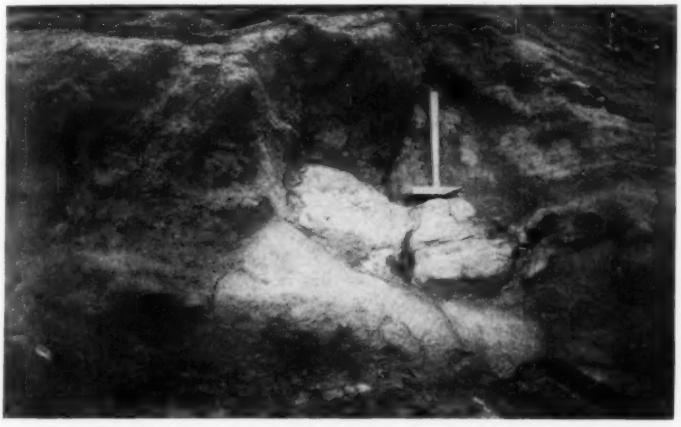


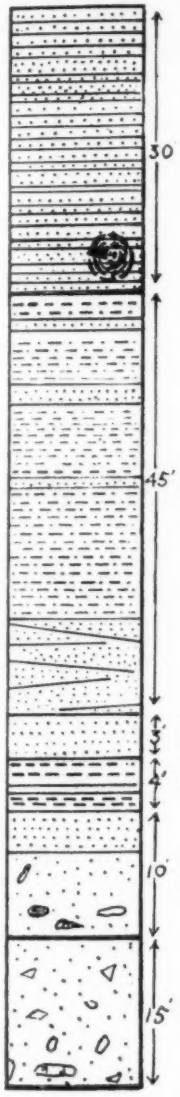
FIG. 8.—Basal sandstone of Oligocene with large included block of decomposed Seca shales (Eocene), Ancon Point.

FIG. 9.—Block of basal breccia containing angular volcanic rocks, etc., Ancon Point.

formably upon the denuded beds of the Tertiary sandstones and shales. The lower beds of the Quaternary consist, not infrequently, of rolled or angular fragments of Tertiary rock which, from their appearance, are of local origin. The Quaternary beach, therefore, has been accumulated *in situ* upon the marine shelf which consisted of Tertiary formations. As a general rule, the Quaternary deposits do not attain any great thickness as individual phases (10–50 ft.); they are normally horizontal, forming extensive peneplains, though occasionally they are tilted at a slight angle—a feature which suggests a post-Quaternary crustal warping of the land mass.

FIG. 10.—Basal breccia bed of the Lower Oligocene, Ancon Point

At least three *tablazo* episodes have been recognized in this present area, each of which represents a successive tectonic uplift of the land surface during Quaternary times. Near Ancon Point, however, only two *tablazo* levels are found: the higher at one hundred and eighty feet, and the lower at about fifty feet above present sea-level. Owing to the enormous amount of subaerial denudation which must have taken place during more recent times, caused principally by the great precipitation of rainfall during the wet seasons, the Quaternary deposits are preserved only as isolated outliers upon the Tertiary rocks, and can be described in the general succession as true erosion remnants.



30 Laminated buff sandstone with tendency to "ball" structure.

45' Chocolate-colored, thin-bedded sandstones and shales, current bedded at base. Coarse and loosely consolidated sandstone.

3' Massive sandstone, lenticular.
Gray, thin-bedded sandstone and shale.

4' Bedded sandstone, buff.

10' Massive coarse sandstone, black fossil wood, thick quartzo-calcitic veins, gastropods, volcanic rock inclusions.

15' Basal breccia, including limestone blocks and fossil wood.

FIG. 11.—Section of Oligocene, at Ancon Point

A full description of the Quaternary formations of Peru, with references to those of Ecuador, has been already published,[1] and observations by the present writer have confirmed the view that these deposits can be correlated quite satisfactorily with the *tablazos* found along the coastal belt of southern Ecuador.

CONDITIONS OF DEPOSITION AND GEOLOGICAL HISTORY OF THE FORMATIONS

The river system which now drains into the enormous estuary known as the Gulf of Guayaquil forms an episode of comparatively recent geologic times, and probably dates from the close of the Quaternary period. The original basin, or channel, into which the contributory rivers flowed from the Andes was in existence shortly after the initiation of the post-Cretaceous uplift, and it is certain that at this period the western flank of the Andean complex formed the coast line of the Pacific.

While the Cretaceous rocks[2] were thus being raised into a mountain chain of great regional extent, the rivers draining the continent were debouching into the sea, thus materially assisting in the formation of the Tertiary sediments. As the majority of the Tertiary rocks found in this area are obviously of shallow water, estuarine, or deltaic origin, it must be assumed that during this epoch the respective basins of deposition were in a state of tectonic subsidence. This differential crustal movement had its complement in the gradual uplift of the Andean system which, at the same time, was being intensively eroded, and the detritus so formed transported into the Tertiary sea.

As stated above, the lithology of both the Oligocene and Eocene strata found in the Ancon Point area shows unmistakable indications of variation in the sedimentation, from shallow water, inland lagoon, estuarine and deltaic conditions. The Oligocene facies, for example, has certain features most of which can be attributed to abnormal fluvial activity during the period of deposition, a fact which suggests exceptionally heavy rainfall upon the continental region of that time.

As previously described, the upper stages of the Lower Oligocene

[1] T. O. Bosworth, *The Geology and Palaeontology of North West Peru* (1922).

[2] T. Wolf, *Geografica y Geologia del Ecuador* (Leipzic, 1892).

contain abundant fragments of volcanic rock, the Ancon white sandstone having a high percentage of pumice, or volcanic ash, in its composition. It can be assumed, therefore, that the Oligocene has been derived probably in part from the denudation of an Eocene land surface, the latter having been intruded by dikes of post-Eocene and pre-Oligocene age.

The contact between the Oligocene and the Eocene beds is defined by an unconformity which in itself shows that a regional uplift took place, resolving the latter temporarily into a land surface. This was denuded considerably before the succeeding subsidence was completed which caused the invasion of the Oligocene sea. As noted in a previous section of this paper, the Upper Eocene strata of this area have been divided into two stages, known as the Seca shale and the Socorro stage, respectively. Owing to the lack of surface outcrops, it is impossible to give any idea regarding the nature of the Lower Eocene strata beyond the fact that a number of boreholes have proved the existence of harder and more compact sandstones. There is evidence also that a slight stratigraphical hiatus occurs between the Seca shales and the Socorro beds, this being probably in the nature of a disconformity. Though the latter is not always clear in the present area, the cliff sections farther to the north, in the province of Manabi, illustrate the phenomenon quite conclusively.

The variations in the lithology between the two sets of strata, however, are indicative of a change in the conditions governing the sedimentation. The Socorro consists mainly of shales with interbedded sandstones, while the overlying Seca beds include finely textured shales practically devoid of arenaceous material. From the uniformity of the constitution of these shales it is possible to assume that they were formed in a deeper basin than the one in which the Socorro beds were laid down. This sea was probably of a lagoon type, and the depositional area was free from the incursion of estuarine detritus.

The close of the Eocene period was marked by a recession of the sea from this area which resulted from a regional uplift of the land surface. The Basal breccia of the Lower Oligocene always contains large blocks of decomposed Seca shale; hence, it is evident that considerable erosion, most probably along a marine beach, took place

before the depression of the land surface began. This later tectonic movement coincided with the sedimentation of the Lower Oligocene strata, and it is possible that during the whole of this period the basin of deposition was gradually subsiding. From the general appearance of the Oligocene rocks it can be inferred that current action was very prevalent, and that most of the material was transported by rivers of great activity. Deltaic accumulations are also not uncommon, and large quantities of fossil wood, breccias, lignite, and lenses of derived volcanic rock all suggest that the erosive power of the rivers debouching into the depositional area was phenomenal.

From the close of the Lower Oligocene to the beginning of the Quaternary most of the formations remained as a defined continental shelf, and became subject to intense denudation. The final tectonic uplift was accompanied by pronounced crustal warping and deformation of the strata, in addition to the intrusion of igneous dikes.

THE STRUCTURE

The Santa Elena peninsula, to the south of which the area under present discussion is situated, is probably the most striking topographical feature of the coast belt. Its directional trend lies to the northwest, and thus it conforms with the coast line forming the northern arm of the Gulf of Guayaquil. The present topography of the peninsula is due fundamentally to outcrops of igneous rock which extend more or less in a line from La Puntilla (the tip of the peninsula) to the southeast for a distance of nearly twenty miles. This igneous "backbone," along with the cherts which are usually associated with the intrusions, has so reinforced the sedimentaries that they persist, in the peninsular form, as the most westerly extension of the Ecuadorian landmass. A similar line of intrusions, with cherts, has been also observed in a locality about twenty-five miles to the north of the present area, this having the same general direction (northwest-southeast) as the outcrops of Santa Elena.

In a regional sense, the major structural folds and zones of shattering are disposed in the same northwesterly direction, though minor cross-flexuring is not uncommon in association with the principal structures. The majority of the local overfolds and reversed faults in the Tertiary formations appear to have been formed

through the influence of a tectonic compression actuated from the northeast, as the strike of the disturbed strata is generally northwest, and in several cases distinct overthrusts occur which indicate clearly the direction of the main tectonic forces.

Most of the igneous intrusions of this region are of post-Eocene and pre-Oligocene age, though farther to the northeast, i.e., along the eastern flank of the Cordillera de Colonche, large igneous masses of post-Miocene and pre-Quaternary age are found. In no case, how-

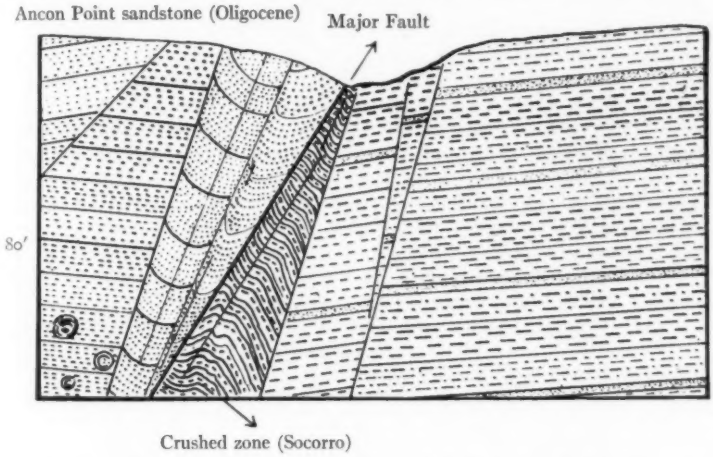


FIG. 12.—Ancon Point sandstone (Oligocene) faulted against Socorro shales (Eocene). Ancon.

ever, have the intrusive rocks penetrated the Quaternary. The field evidence appears to favor the view that the intrusions followed the regional folds and that the main compression from the northeast induced zones of crustal displacement trending northwest and southeast.

Ancon Point itself can be described as a faulted outlier of Oligocene formations, being dislocated from the Eocene beds to the east by a major displacement. The easterly extremity of this fault can be plainly recognized near the settlement (Figs. 2 and 12); and, with subsidiary ramification, it traverses the Point toward the northwest. The trend of the fault line conforms with the general line of folding

in this region, viz., northwest-southeast, and from a study of the structure of the Oligocene formations it is obvious that these beds have been faulted down in their relation to the Eocene. At the same

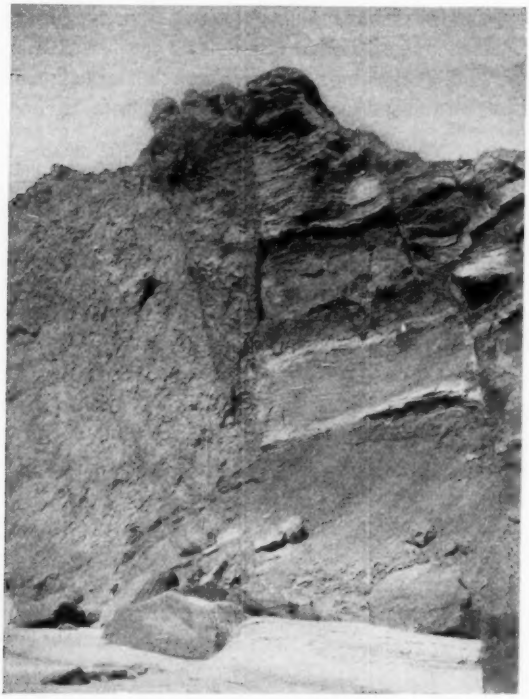


FIG. 13.—Fault contact between Eocene shales (left), and Oligocene sandstones. West of Ancon Point.

time, however, the displacement cannot be great, as faulted inliers of the Eocene shales are found apparently "dragged" between the respective blocks of faulted Oligocene strata. The nature of the fault contact between the Eocene and the Oligocene on the western side of the headland is illustrated by Figure 13 and the similar structure to the east by Figure 12.

As will be seen from the sketch map, the principal fault lines are,

for the most part, accompanied by displacements of a subsidiary nature which have had the effect of dividing the Eocene shales into wedge-shaped blocks, the latter being intimately associated with the Oligocene strata (Figs. 2 and 14).

HISTORY OF THE INCLUDED VOLCANIC ROCKS

The presence of fragments of volcanic rock in the lower beds of the Oligocene has been discussed (pp. 121, 126). With the exception of the clay pebble bed, a unique phase of deposition, no igneous rocks have been recognized as part of the sedimentation of the Eocene. It can be assumed, therefore, that shortly after the close of the Eocene a group of intrusions was developed, probably in association with the zones of major folding. In several localities the dikes can be seen penetrating the Eocene strata, and their outcrops always assume a peculiar spheroidal form as a result of weathering. At La Puntilla, curious lenses of igneous rock are incorporated in the cherts, and these appear to form the fringe of a more deep-seated intrusion, having been extruded through a fissure in the country rock. The basal horizons of the Oligocene contain abundant fragments of volcanic débris, and the hand specimens are identical with the post-Eocene dikes of the peninsula. From the megascopic appearance, and from the proximity of the dikes *in situ* on the mainland, it is obvious that the volcanic rocks now found as part of the sedimentation of the Oligocene have not been derived from a great distance, but from local denudation of the Eocene land surface. The upper part of the Lower Oligocene facies, however, consists of light-colored sandstone (Ancon white sandstone), and a high percentage of this formation is made up of volcanic ash, with small angular fragments of a trachytic type of rock. This stage of the Oligocene has been formed probably from the direct denudation of a

FIG. 14.—Sketch Map of Ancon Point, showing principal faults. Scale: 0.9 inches to 1 mile.

lava flow. The distribution of this sandstone is limited in a regional sense, and the source of the volcanic detritus which makes up the greater part of the rock cannot have been far distant from the area under consideration. The lithology of the formation suggests, therefore, that in post-Eocene and pre-Oligocene times a volcano was in eruption in this region, the lava flows of which were denuded and later consolidated as part of the Oligocene sediments.

PREVIOUS RESEARCH

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Acknowledgments are made to the Board of the Anglo-Ecuadorian Oilfields, Ltd., who have kindly sanctioned the publication of this paper, and to Mr. C. Barrington Brown, Mr. L. W. Berry, and Mr. A. J. Murray, who carried out the original surveys in this region. Figure 1 (map of Ancon Point) has been based largely upon the work of Mr. Murray, who frequently accompanied the author in the field, and who rendered valuable assistance on many occasions.

THE EOCENE AGE OF THE SUPPOSED LATE UPPER CRETACEOUS GREENSAND MARLS OF NEW JERSEY[1]

C. WYTHE COOKE and LLOYD W. STEPHENSON

ABSTRACT

Three formations of the coastal plain of New Jersey, the Hornerstown marl, the Vincentown sand, and the Manasquan marl, which have heretofore been referred to the Upper Cretaceous series, are, on the basis of a new analysis of their contained fauna and the transgressive overlap of the Hornerstown marl on formations of undoubted Upper Cretaceous age, now correlated with the Eocene. The three formations and the overlying Shark River marl, the Eocene age of which has not been questioned, are, on the evidence of common fossil species, correlated approximately with the Pamunkey group (Eocene) of Maryland.

HISTORICAL SUMMARY

The Cretaceous and Eocene formations of New Jersey attracted attention many years ago because of their extensive deposits of greensand, which was used as fertilizer. As early as 1868 the stratigraphic succession was fairly well established and descriptive names had been applied to the different divisions,[2] although place names for the formations were not proposed until the nineties.[3] The current classification, as adopted by the United States Geological Survey in *Bulletin 727*,[4] is based primarily upon the work of W. B. Clark as modified by Knapp and Kümmel.[5] It is shown in Table I.

The stratigraphy and paleontology of the formations below the Shark River were summarized in 1907 by Stuart Weller in "A Re-

[1] Published by permission of the director of the U.S. Geological Survey.

[2] G. H. Cook, "Geology of New Jersey," *New Jersey Geol. Survey* (1868), pp. 900.

[3] W. B. Clark, "A Preliminary Report on the Cretaceous and Tertiary Formations of New Jersey," *New Jersey Geol. Survey, Ann. Rept. for 1892* (1893), pp. 167–245; "Origin and Classification of the Greensands of New Jersey," *Jour. Geology*, Vol. II (1894), pp. 161–77.

[4] G. R. Mansfield, "Potash in the Greensands of New Jersey," *U.S. Geol. Survey Bull. 727* (1922), p. 7.

[5] G. N. Knapp, and H. B. Kümmel, "The Stratigraphy of the New Jersey Clays," *New Jersey Geol. Survey*, Final Rept. 6, 1904.

port on the Cretaceous Paleontology of New Jersey Based upon the Stratigraphic Studies of George N. Knapp," which forms Volume IV of the Paleontology series of the Geological Survey of New Jersey. A critical analysis of the marine faunas led Weller to the conclusion that only two major paleontologic divisions can be recognized, and that the line separating them lies between the top of the Tinton sand and the bottom of the Hornerstown marl. The fauna of the lower division, which he proposed to designate "Rip-

TABLE I

CRETACEOUS AND EOCENE FORMATIONS IN THE COASTAL PLAIN OF NEW JERSEY

System	Series	Formation	Thickness (Feet)
Tertiary.....	Eocene	Shark River marl	11
		Manasquan marl	25
		Rancocas group:	
		Vincentown sand	25–70
		Hornerstown marl	30
		Monmouth group:	
Cretaceous...	Upper Cretaceous	Redbank sand with Tinton sand member at top	10
		Navesink marl	25–40
		Mount Laurel sand	5–60
		Matawan group:	
		Wenonah sand	20–35
		Marshalltown formation	30–35
		Englishtown sand	20–100
		Woodbury clay	50
		Merchantville clay	60
		Magothy formation	25–175
		Raritan formation	150–250

leyian," has many species in common with the Upper Cretaceous or Gulf series of Alabama, Mississippi, and Texas. The higher fauna, which, because of its typical development in New Jersey, he called "Jerseyian," had not been recognized elsewhere in North America, although some of its characteristic species had been identified from the Eocene of Maryland. Because of a supposed similarity of the bryozoan fauna of the Vincentown to that of the Maestrichtian beds of Western Europe, Clark and Weller were led to suggest a correlation of the "Jerseyian" with the Danian of Europe. Weller clearly perceived the faunal differences that distinguish the beds above the Monmouth group from the underlying strata; but, lacking detailed acquaintance with early Eocene faunas, he did not consider the

possible significance of the faunal change as an intersystemic boundary.

In discussing the fauna of the Hornerstown marl, Weller[1] says: "The interesting fact in regard to this fauna is that it is totally different, in its essential characters, from the faunas of the subjacent formations from the Tinton down, and that it is the first appearance of a fauna which has its most typical expression in the Manasquan marl, at the very summit of the Cretaceous series."

On page 171 of the volume cited he says: "The fauna of the Vincentown lime-sand is unique among the Cretaceous faunas of New Jersey, ... although . . . . some of the species of mollusks . . . . occur also in the subjacent Hornerstown marl and in the superjacent Manasquan marl." The Manasquan fauna is described as a recurrence, in its essential characters, of the fauna of the Hornerstown.

A NEW ANALYSIS OF THE FAUNA

Because of the striking dissimilarities between the "Ripleyian" and the "Jerseyian" faunas so clearly brought to light by Weller, Stephenson began to suspect some years ago that the "Jerseyian" might not be Cretaceous at all, but might prove to be Eocene. Opportunity to put this suspicion to the test did not present itself until the last week in October, 1927, when the writers visited all the more important outcrops of the Hornerstown, Vincentown, Manasquan, and Shark River formations. The results of this trip and of a new analysis of the "Jerseyian" fauna appear to prove that all the formations named are of Eocene age.

The "Jerseyian" fauna described by Weller contains about 80 foraminifers, 3 corals, 2 crinoids, 2 asteroids, 15 echinoids, 1 worm, more than 50 bryozoans, 5 brachiopods, 25 pelecypods, 8 gastropods, 2 cephalopods, 3 ostracodes, and 1 cirriped.

The most remarkable feature of this fauna, in view of its supposed Cretaceous age, is the total absence of characteristic Cretaceous species or genera. *Inoceramus*, *Exogyra*, *Trigonia*, *Sphenodiscus*, *Scaphites*, *Belemnitella*, and *Baculites*, nearly all of which are conspicuous elements in the fauna of the Cretaceous formations below

[1] *New Jersey Geol. Survey, Paleontology*, Vol. IV (1907), p. 159.

the Hornerstown, have completely disappeared. These genera did not become extinct at the end of the period represented by the uppermost beds containing them in New Jersey, for they are found in abundance in somewhat younger Cretaceous deposits in Alabama and other Gulf states. It is true that many of the genera represented in the "Jerseyian" fauna would not be out of place in the Cretaceous, but it is equally true that they would be at home in the Eocene or even more recent deposits.

The only species that give a Cretaceous aspect to the "Jerseyian" fauna are *Gryphaea dissimilaris* Weller, which would by most paleontologists be considered a variety of *Gryphaea vesicularis* Lamarck, a common Cretaceous species, and *Gryphaeostrea vomer* (Morton), but both of these species have been recorded from the Eocene Aquia formation of Maryland. Similar forms are not uncommon at several horizons within the Eocene of the South Atlantic and Gulf states.

The eighty Foraminifera listed by Weller were not studied by modern methods, and the identifications cannot be trusted. Dr. J. A. Cushman, to whom we sent material from the Vincentown sand, found nothing with close Cretaceous affinities, but, on the contrary, several species that are very closely related to Middle or Upper Eocene species.

The three corals assigned by Weller to the Manasquan and by Vaughan[1] to the Shark River belong to three genera that are represented by species in the Eocene of Maryland and the Gulf states. The fifteen echinoids from the Vincentown might very well be Eocene; in fact, some of the genera are unknown in American Cretaceous deposits, although common in the Eocene. Nothing like *"Serpula" rotula*, also from the Vincentown, is known from the Cretaceous of America, but there is a very similar species in the Eocene Cook Mountain formation of Texas.

The Bryozoa also indicate the Eocene age of the "Jerseyian" fauna, for seven or eight of the eighteen species reported from the Aquia formation occur in the much more prolific Vincentown sand. Of the five species of brachiopods recorded by Weller, *Terebratula harlani*, one of the most characteristic species of the "Jerseyian," is known elsewhere only from the Eocene of Maryland, although

[1] T. W. Vaughan, *U.S. Geol. Survey Mon. 39* (1900), p. 16.

similar Terebratulas occur in the Lower Eocene (Clayton formation) of Alabama and in the Upper Eocene (Castle Hayne marl) of North Carolina; *Platidia cretacea* Weller, from the Vincentown, is distinguished only by its smaller size from *Platidia marylandica* Clark and Martin, from the Aquia formation; and the other three brachiopods are Eocene types.

The most significant pelecypod yet discovered, one that was not known to Weller, is a cast of a large *Venericardia*, apparently *V. planicosta* var. *regia* Conrad, that could not be mistaken for any known Cretaceous species. *Venericardia planicosta* is one of the most typical Eocene fossils. The variety *regia* occurs in the Aquia formation of Maryland. The cast so identified came from the Hornerstown marl. Among the gastropods is *Caricella plicata* Whitfield. The genus *Caricella*, although common in the Eocene, is unknown in the Cretaceous. The cephalopods are represented by a so-called *Hercoglossa* (which probably is an *Aturia*) and a *Nautilus*. *Aturia* is unknown in the American Cretaceous, but occurs in the Eocene of the South Atlantic and Gulf states.

Three ostracodes are listed from the Vincentown sand. The types of all three came from the Aquia formation of Maryland. They have not been reported from Cretaceous deposits.

A vertebra of a snake collected by Professor Charles Schuchert from the Vincentown sand has been identified by Mr. C. W. Gilmore as *Palaeophis halidanus* Cope, a species described from the Eocene of Monmouth County, New Jersey, and scarcely distinguishable from *Pterosphenus schucherti* Lucas, from the Upper Eocene Jackson formation of Alabama. *Palaeophis* appears to be unknown in the Cretaceous, but occurs in the Eocene of Europe.

The evidence of all classes of organisms, therefore, points to the Eocene rather than to the Cretaceous age of the "Jerseyian" fauna.

THE EOCENE FORMATIONS OF NEW JERSEY AND MARYLAND

The analysis of the "Jerseyian" fauna as a whole brought out its close relationship to that of the Eocene deposits of Maryland. It is now in order to examine more closely the formations in which it occurs in New Jersey and to compare them with the Maryland Eocene.

Hornerstown marl.—The Hornerstown, at the base of the series, consists of 30 feet or less of glauconite, clay, and sand. It lies unconformably upon the Upper Cretaceous and transgresses the Tinton and Redbank sands and the Navesink marl. At the bottom is a zone containing mososaur bones and other massive fossils that have been reworked from the underlying Cretaceous deposits. At the top is a 4–7-foot shell bed containing great numbers of *Gryphaea dissimilaris* and *Terebratula harlani*. The corals, brachiopods, and mollusks that were described from the formation by Weller are listed below:

Flabellum mortoni Vaughan
Terebratula harlani Morton
Terebratulina atlantica (Morton)
Cucullaea vulgaris Morton (based on internal casts and probably incorrectly identified)
Cucullaea compressirostra (Whitfield)
Gryphaea dissimilaris Weller
Gryphaeostrea vomer (Morton)
Modiola subinflata Whitfield
Veniella? decisa (Morton)
Cardium knappi Weller
Caryatis veta Whitfield
"Hercoglossa" paucifex (Cope)

Vincentown sand.—The most characteristic part of the Vincentown is a calcareous sand that is locally hardened into slabs of limestone. It consists in large part of foraminifers, bryozoans, broken echinoids, and other calcareous organisms. The lime sand is interbedded with glauconite-bearing quartz sand. The thickness of the formation ranges from 25 to 70 feet. The fauna of the quartz sand is essentially the same as that of the Hornerstown marl and includes, like the Hornerstown fauna, *Terebratula harlani* as its most common species. Weller lists from the Vincentown sand 46 foraminifers, 54 bryozoans, 15 echinoderms, and the species in the following list:

Rhizocrinus cylindricus Weller
Pentacrinus bryani Gabb
Goniaster mammillata Gabb
Pentaceros asperulus Clark
Serpula rotula (Morton)
Terebratula harlani (Morton)

Cistella beecheri Clark
Cistella plicatilis Clark
Platidia cretacea Weller
Arca quindecemradiata Gabb
Ostrea bryani Gabb
Gryphaeostrea vomer (Morton)
Modiola ovata Gabb
Cardita intermedia Whitfield
Cardium knappi Weller
Isocardia conradi Gabb?
Caryatis veta Whitfield
Gastrochaena americana Gabb (typical occurrence)
Polorthus tibialis (Morton)
Pleurotrema solariformis Whitfield
Clavoscala annulata (Morton)
Perissolax trivolva Gabb
Nautilus bryani Gabb
Cythereis bassleri Ulrich
Bythocypris parilis Ulrich
Cytherella submarginata Ulrich
Scalpellum conradi Gabb

Manasquan marl.—The Manasquan is 25 feet thick. The lower 13–17 feet is dark green and is composed of glauconite, sand, and clay. The upper part of the formation consists of ash-gray fine sand and clay. The Manasquan is said to lie conformably upon the Vincentown sand and to merge imperceptibly into the overlying Shark River marl. The Manasquan fauna, as listed by Weller, includes the following species:

Flabellum mortoni Vaughan
Trochocyathus conoides (Gabb and Horn)
Balanophyllia inauris Vaughan
Terebratulina atlantica (Morton)
Ostrea bryani Gabbi
Modiola johnsoni Whitfield
Periploma elliptica (Gabb)
Veniella? rhomboidea (Conrad)
Etea delawarensis (Gabb)
Crassatellites littoralis (Conrad)
Crassatellites rhombea (Whitfield)
Cardita intermedia Whitfield
Cardium nucleolus (Whitfield)

Caryatis veta Whitfield
Petricola nova-aegyptica Whitfield
Panopaea elliptica Whitfield
Pleurotomaria brittoni Whitfield
Caricella plicata Whitfield
Volutoderma intermedia Whitfield
Rostellites biconicus Whitfield
Pleurotoma farmingdalensis Whitfield

Shark River marl.—The Shark River consists of about 11 feet of speckled gray-green glauconitic sand and clay and contains a few small pebbles. About 75 mollusks, preserved mostly as casts, are described by Whitfield[1] from this bed. In addition to these, 1 mammal, 3 snakes, and 7 fishes are known.[2]

The Shark River was recognized as Eocene by Conrad[3] as early as 1848, and since then disputes as to its age have concerned themselves as to its position within the Eocene series. Clark[4] referred it to the Lower Eocene; Dall,[5] Vaughan,[6] and Harris[7] regarded it as of Claiborne (Lisbon) age.

Pamunkey group.—The Eocene deposits of Maryland, called Pamunkey group by Darton, have been divided by Clark and Martin[8] into the Aquia formation, below, and the Nanjemoy formation, above. Both are highly glauconitic; the Aquia is sandy or calcareous; the Nanjemoy contains considerable clay. The Aquia consists of two members: the Piscataway indurated marl and the Paspotansa greensand marl, which includes hard ledges of limestone. The Nanjemoy, likewise, is made up of the greenish-gray sandy Potapaco clay member and the Woodstock greensand marl member. All the divisions have more or less characteristic faunas, although a few species range throughout the group.

[1] R. P. Whitfield, *U.S. Geol. Survey Mon. 9* (1885), and *18* (1892).

[2] Listed by W. B. Clark, *U.S. Geol. Survey Bull. 83* (1891).

[3] T. A. Conrad, *Philadelphia Acad. Nat. Sci. Jour.*, N. S., Vol. I (1848), pp. 71–72.

[4] W. B. Clark, "Correlation Papers, Eocene," *U.S. Geol. Survey Bull. 83* (1891), p. 80; "Upper Cretaceous Formations of New Jersey, Delaware, and Maryland," *Geol. Soc. America Bull.*, Vol. VIII (1897), p. 354.

[5] W. H. Dall, *U.S. Geol. Survey, Eighteenth Ann. Rept.*, Part II (1898), p. 344.

[6] T. W. Vaughan, *U.S. Geol. Survey Mon. 39* (1900), p. 16.

[7] G. D. Harris, *Science*, N. S., Vol. XLIII (1916), pp. 532–33.

[8] W. B. Clark and G. C. Martin, *Maryland Geol. Survey, Eocene* (1901).

CORRELATION OF THE NEW JERSEY AND MARYLAND DEPOSITS

The Hornerstown marl and the Pamunkey group have the following species in common: *Terebratula harlani*, which occurs in the upper member of the Aquia; *Gryphaea dissimilaris*, in the lower member of the Aquia; *Gryphaeostrea vomer*, which ranges through the Aquia formation and the lower member of the Nanjemoy; and *Venericardia planicosta* var. *regia*, which is restricted to the Aquia. The Vincentown sand contains *Gryphaeostrea vomer*, three ostracodes, and eight bryozoans of the upper Aquia. There is also a *Platidia* which is probably the same as a species in the lower Nanjemoy.

The presence of *Terebratula harlani* and *Gryphaea dissimilaris*, the most common and characteristic species of the Hornerstown, in the Aquia formation is pretty good evidence that the two are of nearly the same age. Also, the presence of similar bryozoan faunas in the Vincentown sand and in the upper member of the Aquia is an indication that these two are the same, and suggests the probability that the Hornerstown and the Vincentown together are equivalent to the Aquia formation. Moreover, the lithology of the formations is in accord with this supposition, for the Hornerstown and the lower member of the Aquia are both greensand marls and the Vincentown and the upper member of the Aquia are both calcareous and contain hard ledges of limestone. A similar correspondence in lithology is found between the overlying formations, for the Manasquan and the lower member of the Nanjemoy contain considerable clay and differ from the other divisions of the series in their gray color; and the Shark River and the upper member of the Nanjemoy are greensand marls. The tentative correlation of the Eocene deposits of New Jersey with the Pamunkey group of Maryland (Table II) is therefore based partly upon the evidence of fossils and partly upon physical similarity.

THE CRETACEOUS-EOCENE CONTACT

The consensus of opinion is that the lowest member of the Pamunkey group of Maryland is not older than the Wilcox group of the Gulf region. If this correlation is correct, the Midway group, which underlies the Wilcox group in Alabama, is not represented

in the Maryland Eocene, for the Pamunkey group rests unconformably upon the Monmouth formation of the Upper Cretaceous. If the correlation of the Pamunkey group with the Rancocas, Manasquan, and Shark River formations of New Jersey is correct, it follows that the Midway group is also unrepresented in New Jersey, and the Cretaceous-Eocene contact both there and in Maryland records a much greater time hiatus than the Cretaceous-Eocene contact in the Gulf region, where the Midway is present.

The reality of the stratigraphic break between the Cretaceous and Eocene deposits of New Jersey is confirmed by diastrophic evi-

TABLE II

TENTATIVE CORRELATION OF THE EOCENE DEPOSITS OF NEW JERSEY AND MARYLAND

New Jersey		Maryland		
Shark River marl		Pamunkey group	Nanjemoy formation	Woodstock greensand marl member
				Potapaco clay member
Manasquan marl			Aquia formation	Paspotansa greensand marl member
Rancocas group	Vincentown sand			Piscataway indurated marl member
	Hornerstown marl			

dence to which reference has already been made. In Monmouth County the Hornerstown marl (Eocene) rests upon the Tinton sand member of the Redbank sand, the youngest division of the Monmouth group (Upper Cretaceous). From north to south the Hornerstown transgresses across the older, more typical beds of the Redbank, finally completely overlapping them, and across the Navesink marl, until at the well-known section at Mullica Hill in Gloucester County the Hornerstown rests upon the still older Mount Laurel sand of the Monmouth group. The base of the Hornerstown marl at this locality is a bed of conglomeratic greensand 2 feet thick, containing great numbers of phosphatic casts of reworked Cretaceous mollusks. This overlap of the Eocene on the Cretaceous accounts for at least a part of the thinning of the Cretaceous deposits from north to south, which has been noted by previous investigators.

ADIRONDACK STUDIES[1]: THE AGE OF CERTAIN OF THE ADIRONDACK GABBROS, AND THE ORIGIN OF THE REACTION RIMS AND PECULIAR BORDER PHASES FOUND IN THEM

JOSEPH L. GILLSON, WILLIAM H. CALLAHAN, and WILLIAM B. MILLAR[2]

ABSTRACT

Stocklike masses of gabbro are a subordinate but very characteristic feature of the Adirondack geology. The age of these numerous masses has been in doubt, since they have been interpreted as intrusive stocks in one quadrangle and as older inclusions in the same country rock in the next. The writers have made a field and laboratory study of a considerable number of these gabbros and have reached the conclusion that they are younger intrusives in the older granite-syenite series, thus agreeing with the views of Kemp and Cushing and the earlier view of Miller. The kelyphitic reaction rims abundant in them and their dioritic border phases are thought to be the result of an attack on the already solid rock by emanations from the gabbro reservoir in depth.

THE PROBLEM STATED

In the pre-Cambrian crystalline rocks of the Adirondack province, in northeastern New York State, a large number of gabbro masses occur. The largest mass is about four miles in diameter, but the majority are small. Their age in relation to that of the other rocks has been in doubt, since they have been mapped as intrusive plugs in one quadrangle, and as older inclusions in the same country rock in the next. In addition to these true gabbros some basic syenites occur that are probably related to them. There are, further, some amphibolite rocks in some parts of the Adirondacks that may be of an earlier age, though, as Cushing[3] said, the smaller masses and dikes of gabbro are always found in the amphi-

[1] The Department of Geology of the Massachusetts Institute of Technology has had several of its students working on problems in the Adirondack Mountains. This is the first of a series of reports on these studies.

[2] Associate professor, and former students, respectively, Department of Geology, Massachusetts Institute of Technology.

[3] H. P. Cushing, "The Geology of the Long Lake Quadrangle," *New York State Museum Bull. 115* (1906), p. 483.

bolite condition, and this more metamorphosed condition seems to argue a greater age, though it is possible to explain it as due to local causes. Such amphibolites have recently been described by Smythe and Buddington[1] in their report on the Lake Bonaparte

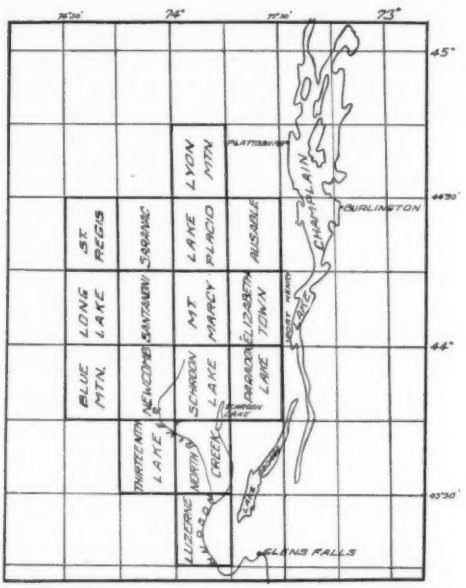

FIG. 1.—Outline map of the Eastern Adirondack region showing a number of the quadrangles.

quadrangle. The masses of true gabbro considered in this paper are those found widely distributed in the North Creek, Schroon Lake, Luzerne, Elizabethtown, Port Henry, Lake Placid, Paradox Lake, Newcomb, and the adjacent quadrangles surrounding the central anorthosite core of the Adirondack province. The number of these masses is noteworthy: sixty-one are reported in the North Creek quadrangle, sixty-three in the Luzerne, twenty-five in the Schroon Lake, seven in the Lake Placid, seven in the Long Lake, five

[1] C. H. Smythe and A. F. Buddington, "The Geology of the Lake Bonaparte Quadrangle," *New York State Museum Bull. 269* (June, 1926).

in the Paradox Lake, and thirty-one in the Elizabethtown and Port Henry quadrangles.

The geological column in the Adirondacks, after Kemp,[1] is as follows:

- Pre-Cambrian.....
  - Algoman intrusives...
    - Basaltic diabase dikes
    - Gabbro-syenite dikes
    - Gabbro
    - Syenite-granite series
    - Anorthosites..
      - Whiteface type
      - Marcy type
  - Grenville series.....
    - Crystalline limestones
    - Quartzites
    - Paraschists
    - Paragneisses

It was generally believed prior to 1916 by Kemp,[2] Cushing,[3] and Miller[4] that the gabbro masses were younger stocklike intrusives in the granite-syenite series, and considerable evidence was advanced by them to prove this contention. In 1915–16 Miller, while engaged in field work in the Lake Placid quadrangle, began to doubt this age interpretation. In his study of the Luzerne quadrangle published in 1923, all the gabbro masses are considered to be older inclusions in the granite-syenite series,[5] although no new evidence is offered to explain in a different manner his observations of the preceding years. In the North Creek quadrangle the sixty-one masses of gabbro are mapped as intrusive stocks in the granite, while in the adjacent Luzerne quadrangle the sixty-three masses of gabbro are considered to be inclusions in the same granite. That there was still some doubt about the matter even in Miller's mind is indicated

[1] J. F. Kemp and R. Ruedemann, "Geology of the Elizabethtown and Port Henry Quadrangles," *New York State Museum Bull. 138* (1910), p. 52.

[2] *Ibid.* (1910), pp. 52–53.

[3] H. P. Cushing, "Geology of the Northern Adirondack Region," *New York State Museum Bull. 95* (1905), pp. 330–31.

[4] W. J. Miller, "Geology of the North Creek Quadrangle," *New York State Museum Bull. 170* (1914), pp. 26–27.

[5] W. J. Miller, "Geology of the Luzerne Quadrangle," *New York State Museum Bulls. 245–46* (1923), p. 16.

by the fact that in 1923[1] he doubted if any of the gabbros in the whole Adirondack region are of post-syenite-granite age, while in 1926[2] he reminded the reader that throughout the Adirondacks certain bodies of true gabbro are definitely known to be younger than the syenite-granite series.

A very striking feature of these gabbros is the presence in them of peculiar reaction rims or kelyphitic borders.[3] These have frequently been described, perhaps first by Kemp.[4] As they occur also in the anorthosite, a possible relation between the gabbro and the anorthosite is suggested. Another striking feature of the gabbros is a fine-grained, almost schistose border phase, which Miller[5] and Cushing[6] called amphibolite, but which the present authors are calling the diorite phase.

The present study is an attempt to give further evidence as to the relative age of these gabbro masses, and to suggest an explanation of their peculiar features.

DESCRIPTION OF THE GABBROS

GENERAL FEATURES

Speaking generally, the gabbros are medium to coarse grained, dark-green rocks with a poorly defined ophitic texture. Although found with gneissic rocks, they are themselves massive, and, except very locally, devoid of conspicuous gneissic structure. In mineral composition the gabbros consist of plagioclase, augite, hypersthene, hornblende, biotite, garnet, apatite, titanite, magnetite, and ilmenite, and a few are said to contain, in addition, olivine. Both the plagioclase and the augite are present in two generations: an earlier

[1] *Ibid.*, p. 16.

[2] W. J. Miller, "Geology of the Lyon Mountain Quadrangle," *New York State Museum Bull. 271* (1926), p. 12.

[3] "Reaction rims may be further classified as coronas when produced by primary magmatic action, and as kelyphitic borders when secondary post-magmatic action is concerned" (G. W. Tyrrell, *The Principles of Petrology* [1926], p. 94).

[4] J. F. Kemp, "Gabbros of the Western Shore of Lake Champlain," *Bull. Geol. Soc. America*, Vol. V, (1894), pp. 218–21.

[5] W. J. Miller, "Geology of the Lyon Mountain Quadrangle," *New York State Museum Bull. 271* (1926), p. 14.

[6] H. P. Cushing, "Geology of the Long Lake Quadrangle," *New York State Museum Bull. 115* (1906), p. 483.

pyrogenetic generation, and a later metasomatic one. The earlier plagioclase, labradorite, occurs in large crystals of lathlike form which contain in great abundance minute dark inclusions giving the mineral a dark blue color. The labradorite is replaced more or less completely, in every specimen examined, by anhedral grains of glassy andesine, free from these inclusions. This replacement was formerly considered to be a granulation as a result of crushing, and the rocks on that account were supposed to have been severely acted upon by dynamic metamorphism. The earlier augite also contains dark inclusions in the plane of the front pinacoidal parting, and is, therefore, diallage. The later augite occurs in smaller grains and is free from the parting and the inclusions.

At nearly every point the rocks are fresh, containing locally only a small amount of brownish or greenish serpentine in the pyroxenes. Such alteration minerals as epidote, chlorite, sericite, and uralite are absent.

THE REACTION RIMS

The reaction rims, or kelyphitic borders, occur in the normal phase of all the gabbro masses. The dark minerals are commonly grouped into concentric aggregates, in which a hull or (in section) a rim of one mineral entirely, or almost entirely, surrounds another, or is associated with it in an irregular or bizarre fashion. In many cases successive rims or hulls occur. Since garnet is present in many of these rims, they are commonly described as garnet reaction rims.

Miller[1] has made the following observations on the rims found in the gabbros in the North Creek quadrangle:

> Reaction or corrosion rims, which are well known in many basic rocks, are exhibited in a truly remarkable manner in the North Creek gabbros. . . . .
>
> The following nine types or reaction rims comprise most of those noted by the writer in the North Creek gabbros: (1) ilmenite surrounded by hornblende; (2) diallage surrounded by hornblende; (3) augite surrounded by hornblende; (4) hypersthene surrounded by garnet; (5) hypersthene surrounded by successive zones of biotite and hornblende; (6) olivine with successive zones of hypersthene, hornblende, and garnet; (7) olivine with successive zones of hypersthene, biotite, and garnet; (8) hypersthene with successive zones of biotite, feldspar, and garnet; (9) ilmenite with successive zones of biotite, hornblende, garnet, and biotite.

[1] W. J. Miller, "Geology of the North Creek Quadrangle," *New York State Museum Bull. 170* (1914), p. 31.

The authors noted most of these occurrences, and in addition several more, as follows: (1) Ilmenite with successive zones of biotite, hornblende, augite and garnet. (2) Augite surrounded by successive zones of anhedral feldspar and garnet. (3) Graphic intergrowths of garnet and pyroxene surrounded feldspar and augite, or augite alone. The pyroxene, so included, is always in the inner side of the garnet rim. Graphic intergrowths of pyroxene in feldspar, hornblende in garnet, biotite in garnet, biotite in hornblende, and biotite in feldspar were also observed. (4) Hornblende surrounded by garnet. (5) Diallage partially surrounded by hypersthene. (6) Garnet encircling and cross-cutting an aggregate of feldspar grains in which a very few small grains of a ferro-magnesian mineral occur. This shows that garnet could form a circular rim without any relation to a ferromagnesian nucleus. (7) Garnet surrounded by hornblende and biotite.

The great variety of combinations of minerals in these structures indicates that they are not due to a simple reaction between a few primary minerals, and without addition of material.

Other interesting observations made by the writers on the association of minerals in the gabbros were:

The labradorite is replaced, at least to some extent, by andesine in almost every grain. The replacement is most pronounced along the borders of the grains, but is found along cleavage cracks, and haphazardly. This replacement is made conspicuous because of the accompanying elimination of the minute dark inclusions which occur in the primary mineral, presumably as a result of ex-solution. Their elimination, and the change in composition of the feldspar from labradorite to andesine, indicates an addition and a subtraction of material (see Fig. 2).

Garnet replaces feldspar along cleavage cracks and also in the most haphazard manner. There is no relation between the occurrence of garnet and the association of ferromagnesian minerals and feldspar as suggested by Kemp[1] and Roesler.[2]

[1] J. F. Kemp and Rudolph Ruedemann, "Geology of the Elizabethtown and Port Henry Quadrangles," *New York State Museum Bull. 138* (1910), p. 55.

[2] M. Roesler, "Geology of the Mount Marcy Quadrangle," *New York State Museum Bulls. 229–30* (1920), p. 45.

Apatite occurs in stout prisms and in long needles which cut across grains of biotite and hornblende, from one into another, or across adjacent grains of andesine. This association suggests the late formation of apatite by pneumatolytic action.

FIG. 2.—This shows the relics of the coarse diabasic texture of the normal gabbro, and the dusty primary minerals, labradorite and diallage. These have been replaced by a later generation of andesine, garnet, augite, hypersthene, biotite, hornblende and magnetite. These are the minerals, and their size and shape is the same, as found in the diorite border phase. *L*=labradorite; *G*=garnet; *B*=biotite; *D*=diallage; and *A*=andesine. Traced directly from a photomicrograph. Magnification 19 diameters.

Minute blebs of green spinel occur in the glassy andesine in some specimens. Their minute size and association is not that of the pyrogenetic spinel common to ultrabasic rocks, but the grains resemble rather the grains of spinel found in the contact-metamorphosed rocks of Blue Hill, Maine, described by Williams.[1] They suggest pneumatolytic action in the gabbros.

The magnetite and ilmenite, which in many cases occur in the

[1] R. M. Williams, "Contact Metamorphism of the Ellsworth Schist at Blue Hill, Maine," thesis presented to the faculty of the Massachusetts Institute of Technology in partial fulfilment of the requirements of the degree of Master of Science, 1927.

centers of kelyphitic structures, show in many cases an unmistakable deuteric form,[1] as is clearly shown in Figure 4.

All of the grains in the reaction rims have an anhedral or subhedral form. Although no paragenetic sequence could be established that would hold throughout all of the examples studied, evidence

FIG. 3.—A typical example of a reaction rim. The outer zone, marked *G* is garnet, the second zone marked *A* is clear, allotriomorphic andesine crystals of small size, and the inner kernel is augite and hornblende. Minute blebs of apatite are too small to show. *H* is hornblende. Traced directly from photomicrograph. Magnification 61 diameters.

that the minerals of the reaction rims formed by replacement, and in a sequence of some sort, was given by the position and shape of the grains and their mutual boundary relations.

In no place do the reaction rims collectively, or the grains of single rims individually, suggest severe dynamic action during their development. Grubenmann and Niggli[2] have concluded that stress

[1] J. L. Gillson, "Granodiorites of the Pend Oreille District of Northern Idaho," *Jour. Geology*, Vol. XXXV (1927), p. 23.

[2] U. Grubenmann, and P. Niggli, *Die Gesteinsmetamorphose* (1924), p. 165.

is only the catalytic agent increasing the speed of reaction, but that solutions must be present in order for a reaction to take place at all.

In short, the reaction rims appear to be the result of a reaction of the pyrogenetic minerals of the gabbro with solutions which have passed upward through the solid, but still hot rocks.

GARNET
GARNET
H
H
H

grained. The border rock is somewhat schistose, but this apparent schistosity is hardly visible in the thin sections seen under the microscope. The plane of this schistosity is everywhere parallel to the contact, and at this place is nearly at right angles to the gneissic structure of the granite country rock.

The microscopical study of the gradational zone and the border phase of this and other masses showed the changes in mineral composition and texture found on passing from the central part of a mass outward. The labradorite of the main mass becomes less abundant, andesine taking its place, and the reaction-rim structures disappear. The mineral composition of the diorite border phase, however, has just the mineral composition of these reaction rims, and their allotriomorphic texture. Not only are the mineral species the same, but the optical properties of these minerals in the border phases are identical with those in the main mass.

That the character of the border phase of the gabbro masses is not related to the granite, which is the country rock of most of them, is proved by the finding of such border phases in a gabbro dike, cutting gabbro, in some outcrops $1\frac{1}{4}$ miles southwest of the village of Gailey Hill in the Luzerne sheet. This gabbro dike, in spite of its relatively minor lateral dimension, shows the same sort of gradation of texture and mineral composition as the larger masses. It differs only in that the inner portion is similar to the gradational rock of such a mass as that near Thurman, rather than to the normal phase.

THE PEGMATITES ASSOCIATED WITH THE GABBROS

In many places pegmatites of dioritic habit are associated with the gabbros. Miller[1] considered them to be satellites of the gabbro until his change of view as to the relative age of those rocks made him relate them to the granite. The relation of some of the pegmatites to gabbro is shown at places, as near Thurman and near Gailey Hill, where the pegmatite contains hypersthene, hornblende, garnet, and biotite with optical properties almost the same as those possessed by these minerals in the gabbro. Hypersthene was not seen in the granite-syenite series, and garnet is rare. The hornblende of the granite has distinctly different properties from that of the gabbro.

[1] W. J. Miller, "Pegmatite, Silexite, and Aplite of Northern New York," *Jour. Geology*, Vol. XXVII (1919), p. 49.

Thus, the finding of such pegmatites cutting the gabbro is no evidence that the gabbros are inclusions in the granite, as believed by Miller.[1] The pegmatites are simply the last stages of the magmatic action which began with the intrusion of the gabbro magma and continued as a distillation of vapors which recrystallized the basic rock into a dioritic one, more or less completely, and in places formed pegmatite dikes.

EXPLANATION OF AN APPARENT INJECTION OF GABBRO BY GRANITE

Miller[2] describes in some detail a series of outcrops in the east-central part of the Luzerne quadrangle, where he considered the gabbro to be injected by granite. He cites it as one of the most convincing illustrations of the later age of the granite. The locality is along the west side of the state highway, two-thirds of a mile southeast of Gailey Hill and two miles east of the Hudson River. At the north end of the series of outcrops the gabbro is well exposed at its contact with the gneissic granite. The plane of schistosity of the border phase of the gabbro cuts across that of the pronounced gneissic structure of the granite, and back from the contact the gabbro has no visible gneissic structure. Both the gabbro and the granite are cut by quartz-rich pegmatites containing garnet, graphic tourmaline, and pyroxene.

A quarter of a mile southwest of the first locality is a second contact between gabbro and granite. A small gabbro dike with still smaller off-shooting tongues cuts into the granite, and these have chilled fine-grained margins at the contact, but become coarser away from the granite (Fig. 5).

About 50 feet east of this outcrop is one of granite containing narrow and broad bands of a black rock. Miller cites it as an example of gabbro intimately cut by granite (Fig. 6). The mineral composition of the dark bands is, however, that of the granite, and not of the gabbro. The hornblende and biotite of the dark bands and of the normal granite are the same, and quite distinct from the varieties of these minerals in the gabbro. Hence this locality does not show gabbro intimately injected by granite, as interpreted by Miller, but

[1] W. J. Miller, "Geology of the Luzerne Quadrangle," *New York State Museum Bulls. 245–46* (1923), pp. 18–19.

[2] *Ibid.*, pp. 19–20.

banded granite-gneiss, which 50 feet away is clearly intruded by gabbro. Thus, possibly, is explained one of the most confusing outcrops giving evidence on this problem.

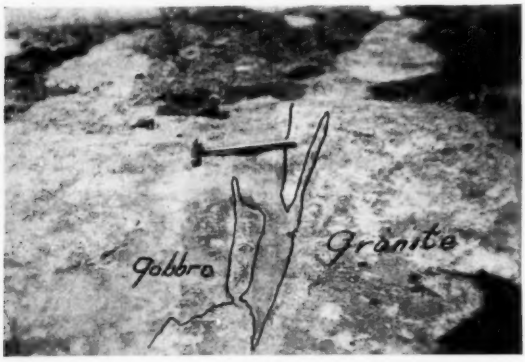

FIG. 5.—Photograph of tongues of gabbro with chilled margins in granite, which is coarse grained to the contact. Second outcrop at Gailey Hill area.

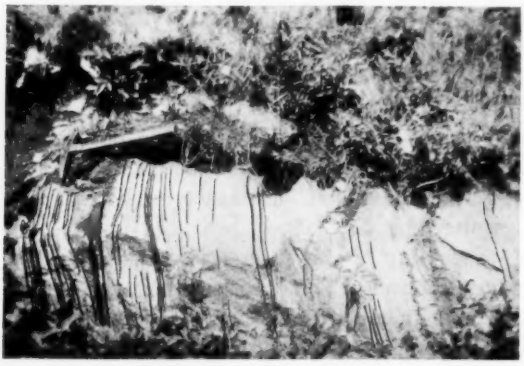

FIG. 6.—Photograph of outcrop along roadside 50 feet from place shown in Figure 5. This is banded gneissic granite, and not gabbro intimately injected by granite, as inferred by Miller.

CONCLUSIONS

When Miller considered the gabbros to be intrusive, he thought that their more acid margins were due to assimulation of the granite

by the gabbro.[1] When he changed his view as to their age, he explained the amphibolite border phase as follows: "A reasonable interpretation is that the finer-grained border portion of the gabbro was produced by granulation due to the pressure of the granite intrusion, ... the basic feldspar was made more acidic."[2]

In regard to the genesis of the reaction rims, Kemp[3] has cited a gabbro that had been somewhat squeezed so that secondary garnets had developed in quantity. Miller[4] suggested that the garnet was formed in part from the feldspar. Roesler[5] accounted for the garnet in the reaction rims by a chemical reaction between the feldspar and the ferromagnesian minerals induced by dynamic metamorphism. A very excellent summary of the ideas concerning the origin of these structures has been given by Sederholm,[6] who concludes: "The process by which the coronites have originated has not consisted exclusively in a reaction between the adjacent minerals. These minerals have supplied only a part of the constituents of the coronas, while another part has been transported in solution from more distant places of the same rock mass."

The authors are in hearty accord with this explanation. They propose the following explanation of the manner of formation of these gabbros:

1. The gabbro masses were intruded after the period of intense dynamic stress as ordinary basic igneous rocks of simple mineralogical composition, consisting essentially of labradorite, augite, and in places containing olivine. This intrusive interpretation is favored by the elliptical cross-section of many masses, and the massive

[1] W. J. Miller, "Geology of the North Creek Quadrangle," *New York State Museum Bull. 170* (1914), p. 27.

[2] W. J. Miller, "Geology of the Lyon Mountain Quadrangle," *New York State Museum Bull. 271* (1926), pp. 14–16.

[3] J. F. Kemp, "Titaniferous Iron Ores of the Adirondacks," *19th Ann. Report, U.S. Geological Survey*, Part 3, pp. 1897–98.

[4] W. J. Miller, "Geology of the North Creek Quadrangle," *New York State Museum Bull. 170* (1914), p. 31.

[5] M. Roesler, "Geology of the Mount Marcy Quadrangle," *New York State Museum Bulls. 229–30* (1920), p. 45.

[6] J. J. Sederholm, "On Synatectic Minerals," *Bull. Comm. Geol. Finlande*, No. 48 (1916), p. 41.

nature of these basic rocks within a granite itself very gneissic is convincing evidence that the rocks were not present during the period of stress. The intrusive nature is further confirmed by the occurrence of dikes or tongues of gabbro, with chilled contacts, in coarse-grained granite at the locality southeast of Gailey Hill. The granite was never seen cutting into the gabbro, and no case was observed where the granite at the contact with the gabbro was any finer grained than that at some distance from the contact.

2. After the rock became solid, or nearly solid, a distillation of volatile constituents came up from the chamber from whence the gabbro had come. These emanations passed through the whole mass of the rock, forming peculiar reaction rims, but they caused most recrystallization along the borders of the gabbro masses and, passing out into the granite, formed pegmatite masses usually of a dioritic type. The mineral composition of the pegmatite associates it with the gabbro, as does the abundance of the pegmatite around the gabbro masses. Convincing evidence that these volatile emanations originated within the gabbro mass is given by the presence of the reaction rims and border phases in all of the gabbro masses, whether found in granite, anorthosite, or other gabbros. Furthermore, the presence of the reaction rims within gabbro masses of large size, as the one at Texas Ridge in the Schroon Lake quadrangle, and in the main mass of the anorthosite, shows that these reaction rims and related phenomena are not the result of contact metamorphism by the granite, which on that account would be inferred to be younger.

3. The recrystallization resulting from these emanations eliminated the original dusty pyroxene and labradorite and substituted hornblende, biotite, a new generation of augite, hypersthene, andesine, and magnetite, and thus formed, when the process was complete, a rock of dioritic composition with allotriomorphic texture. An apparent schistosity in the diorite phase, found at the contacts of the gabbro plugs, must indicate that there was some movement at the contacts of the solid, or nearly solid, rock caused by unrest within the plugs, not by external regional metamorphism.

Where the process was not carried to completion, as throughout the body of the larger masses, it resulted in those peculiar reaction rims found in all. The shape of these reaction rims is not readily

explained, for in many instances the structures in question are not reaction rims at all, since they surround no single grain; and what is most surprising, in many cases the younger minerals are found progressively toward the center of the structures. Their unmistakable connection with volatile emanations is indicated, however, by the fact that the minerals formed in a progressive sequence, by the association with or in them of long needles of apatite, of the same garnet as found in the pegmatites, and especially by the magnetite and ilmenite. The size and shape of the grains of these latter minerals, as shown in Figure 6, gives the most convincing evidence that the grains are truly deuteric,[1] a conception borne out by the bodies of workable magnetite ore found in the Adirondacks which Kemp believed to be the products of pneumatolytic action from these same gabbros.

In short, the gabbro masses are intrusive stocks or plugs which, because of the upward passing of volatile emanations given off from the main reservoir in depth, have had their original simple mineralogical composition changed.

The writers wish to express their thanks to Messrs C. C. Adams, D. H. Newland, and C. A. Hartnagel, of the New York State Museum, who very kindly read the manuscript and made valuable suggestions.

[1] The senior author has elsewhere discussed the evidence afforded by the shape of grains in igneous rocks as proof of their post-magmatic or deuteric formation (J. L. Gillson, "Granodiorites of the Pend Oreille District of Northern Idaho," *Jour. Geology*, Vol. XXXV [1927], p. 23).

GRAVEL ON THE HIGHLAND RIM PLATEAU, AND TERRACES IN THE VALLEY OF CUMBERLAND RIVER[1]

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ABSTRACT

Two patches of gravel on the Highland Rim Plateau of Tennessee are interpreted as deposits of the old Cumberland River formed when it meandered on a plain several hundred feet above the bottom of its present incised meandering valley. The pebbles in the gravel bed were probably derived from conglomerates of lower Pennsylvanian age which were eroded from areas to the eastward. Other pebbles are found on rock terraces and in alluvium within the valley of Cumberland River, which may be from re-worked deposits of gravel comparable to those noted, or in part directly from the Pennsylvanian conglomerates.

INTRODUCTION

There are two small patches of gravel on the Highland Rim Plateau 5½ miles south of Celina, Tennessee, and about 2 miles east of Baptist Ridge School on the Butlers Landing-Hilham road. They are thus near the east margin of the Gainesboro quadrangle, whose north boundary is 10 miles south of the Tennessee-Kentucky line. Adjoining on the north is the Thompkinsville quadrangle, Kentucky-Tennessee. The Lillydale quadrangle borders the Thompkinsville quadrangle on the east, and the Standingstone folio includes a map on the scale of 1/125,000 of the area south of the Lillydale quadrangle and east and southeast of the Gainesboro quadrangle.

The area around Gainesboro is a part of the greatly dissected portion of the Highland Rim Plateau. The whole quadrangle lies within the drainage system of Cumberland River which traverses the area and swings in ingrown meanders[2] 400–600 feet below the

[1] Published with permission of the state geologist of Tennessee. The data upon which this article is based were obtained during the field season of 1926.

Dr. Lusk's lamented death on July 27, 1927, cut short a scientific career of much promise.—ED.

[2] Meanders that have been developed or have been accentuated by lateral shift coincident with down-cutting. Reference may be had to the original definition of this

general level of the plateau, here 900–1,100 feet in altitude. The larger streams likewise meander, a fact to be noted especially in observing the courses of Roaring River and its tributaries, Spring Creek and Blackman Fork, Jennings Creek, and Mill Creek. All the streams, except those that merely fresco the surface of the plateau in the extreme southeastern corner of the quadrangle, occupy deep and narrow valleys with abrupt concavo-convex profiles at their heads. The valleys of the larger streams are separated by narrow linear ridges with numerous long irregular fingers that branch off at large angles to act as divides for the smaller streams and hollows. Many of these lesser ridges in turn have apophyses projecting between the smallest hollows. A straight traverse through the area in any direction would be a tiring succession of steep climbs to the top of a rounded shoulder or a narrow flat ridge, each followed by an abrupt plunge to the bottom of a deep valley with little or no flood-plain. Yet if the course of the traverse might depart from a straight line, the relatively flat plateau or the devious course of a stream might be followed for many miles without notable changes in altitude.

The lowest elevatian in the quadrangle is in the southwest corner where the valley of Cumberland River is about 460 feet above sea-level, while the highest is on the eastern boundary two miles east of Elpardo at an altitude of about 1,150 feet.

The flood-plain of Cumberland River, from 2,000 to 4,000 feet in width, is an extension of the physiographic surface of the Central Basin, but the generalized boundary between the Highland Rim and the Central Basin traverses the quadrangle southeast of the Gainesboro area.

The surface of the Highland Rim Plateau rises slightly from its lowest altitude adjacent to the valley of Cumberland River, both toward the west and toward the east. The most extensive areas of upland are in the eastern and southern parts of the quadrangle. The

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term in the article by John L. Rich, "Certain Types of Stream Valleys and Their Meaning," *Jour. Geol.*, Vol. XXII (1914), pp. 469–97. The term is also employed by Raymond C. Moore in his article "Origin of Inclosed Meanders on Streams of the Colorado Plateau," *Jour. Geol.*, Vol. XXXIV (1926), pp. 29–57.

eastern edge of the quadrangle is 12–20 miles from the foot of the Cumberland Plateau, the greater distance being in the north.

The Fort Payne formation of lower Mississippian age is at the surface of the plateau throughout the area of the Gainesboro quadrangle and much of the adjacent areas, although younger Mississippian formations appear as the rocks descend to the north, west, and east from this area. Beneath the Fort Payne, a green shale, varying in thickness from a few inches to one or two score feet, lies upon the Chattanooga shale. In parts of the Lillydale and Thompkinsville quadrangles, the New Providence formation or Ridgetop shale (or both) appears below the Fort Payne formation. Lying below the Chattanooga shale, and for the most part structurally conformable, the Leipers, Catheys, and Cannon strata of Ordovician age are separated from it by a disconformity. The rocks of the region are gently arched in a northeastern extension of the Nashville Dome.

THE GRAVEL DEPOSITS

The total area of the deposits of gravel noted above is 2 or 3 acres. They cover the tops of two low hills and lie upon the eroded Fort Payne formation. The thickness of the gravel bed is only a few feet. The pebbles are very abundant in a sandy, red clay matrix and are accompanied by a few worn fossils from the Fort Payne and overlying beds. The individual pebbles range in diameter from a quarter of an inch to a maximum dimension of an inch and a half. Nearly all are well smoothed, and the smaller pebbles are very well rounded. They are composed chiefly of clear or milky quartz. Some of the quartz is formed of unshattered and interlocking crystals, some is shattered, some clearly shows combed vein structure, etc.

These two patches of gravel are remnants either of a general sheet of gravel that once blanketed a large part of the Highland Rim Plateau, or channel deposits of an ancient river. In support of this latter alternative, it may be noted that the patches are but $3\frac{1}{4}$ miles from the present course of Cumberland River, whose meander loops with a swing of $2\frac{1}{2}$–3 miles now are incised 400 feet or more below the general level of the plateau. The width of the meander belt on the surface of the plateau prior to the incising of the river was about a mile less than the present swing of the meanders,[1] but even so,

[1] This figure is obtained by subtracting from the length of the present meanders the length of slip-off slopes on spurs which project into meander bends.

was probably great enough to permit the gravel localities to be well within the swing of the meander belt of the old Cumberland River. If the river were restored to its former surface, slightly above the

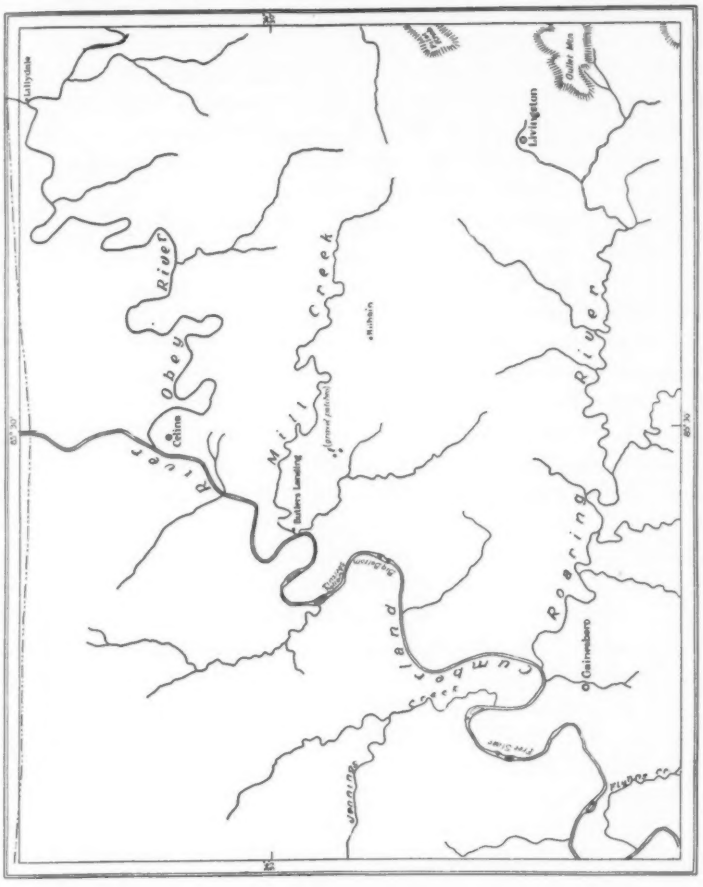

FIG. 1.—Map showing location of gravel patches, and stream meander patterns of an area in north Middle Tennessee.

present plateau, and the meander belt were to be shifted one and one-half times its present width (or twice its former width), these gravel areas would be within the swing of the meanders. (See accompanying map, Fig. 1.)

No other patches were observed upon the plateau, although it is likely that there are others that have been missed. Well-sorted smaller pebbles like those described above, but more perfectly rounded, are at various altitudes within the main valley of Cumberland River and in the valley of Obey River which enters the Cumberland at Celina. These smaller pebbles lie upon the soils that cover rock terraces, and are also in a red clayey alluvium. This alluvium is distinguished from the red residual clay of the Carboniferous and Ordovician limestones by the presence of a small amount of sand and the very well-rounded quartz pebbles.

Some of the hills in the meander spur between Seven Sisters Bluff and Tinsleys Bottom are deeply covered with alluvium, if not entirely composed of it. The same is true of the next spur downstream with Big Bottom on the inner side of the meander. Likewise this is so in "Free State," lying on the inner side of the meander downstream from Stone. The hills referred to are from 100–200 feet higher than Cumberland River. In a gulley on one hill north of Tinsleys Bottom, instead of the more common red alluvium, well-laminated shaly clay is exposed for about 20 feet. This also yields scattered quartz pebbles. This material is more than 100 feet above the river. Pebble-sprinkled alluvium may be found up to an altitude of just under 700 feet north of Tinsleys Bottom and at about the same or slightly lower altitudes at many places downstream. This alluvium is in the Barksdale Bend spur on Obey River, and the topographic map of the Lillydale quadrangle shows remnants of a definite terrace at the altitude of 700 feet and slightly higher. This is the best-preserved level along Cumberland River above the present flood-plain within the area of the Thompkinsville and Gainesboro quadrangles.

There are other terraces along the river both above and below the one at 700 feet. Those above are planed rock surfaces and have no more than a doubtful deposit of pebble-bearing alluvium, although diligent search is usually rewarded by the finding of scattered quartz pebbles. If there is any pebble-bearing alluvium along the courses of Roaring River and Jennings Creek it was overlooked. The 700-foot level may be satisfactorily recognized along Roaring

River but not along Jennings Creek or the smaller tributaries such as Flynn Creek. The Lillydale topographic map shows a fairly well-defined terrace along Obey River at an elevation of 800 feet.

The pebbles noted bear a close resemblance to those studied by the writer in the Rockcastle conglomerate member of the Lee formation of Pennsylvanian age which outcrops at the surface of the Cumberland Plateau at Jamestown, and eastward therefrom. The Cumberland Plateau has a general elevation of 1,600 feet in the vicinity of Jamestown. The nearest outliers of a conglomerate which might be the source of the pebbles in the patches on Baptist Ridge are in the Lee formation about 15 miles to the east, in remnants of the Cumberland Plateau around Livingston, Tennessee (see Fig. 1). At Jamestown, 22 miles east of Livingston, about 1,000 feet of strata lie between the Rockcastle conglomerate member and the Fort Payne formation; the regional dip has carried the beds down about 500 feet lower than they are at Cumberland River.

GENERAL CONCLUSIONS

The evidence so far considered points rather definitely to the conclusion that the old Cumberland River meandered on a surface now elevated and forming the dissected Highland Rim Plateau. Its meander belt was about three-fourths or two-thirds the swing of its present ingrown meanders. Tributaries which were dissecting the Cumberland Plateau transported pebbles probably derived from conglomerates of lower Pennsylvanian age. Some of these pebbles were deposited as bars in the channel of the main stream, along with worn fossils from beds nearer at hand. Most of the gravel deposits were eroded by the short tributaries that developed following initial rejuvenation. Such as did remain have protected the portion of the plateau surface which they covered so that solution and sheet erosion have been least effective there, hence the very low gravel-topped hills on the somewhat-lowered plateau surface. These two patches of gravel on the Highland Rim Plateau were probably deposited during the Eocene period. The gravel must have been deposited near or after the close of the Cretaceous period if this part of the Highland Rim Plateau surface was formed during that time. (The

Tuscaloosa formation of Upper Cretaceous age lies on this surface in West Tennessee.[1])

As Cumberland River became incised, successive terraces were developed, showing that the process of down-cutting was not a steady one. The most marked interruption to continued lowering of the valley floor is evidenced by the relatively thick deposit of alluvium which is now represented in hills of intermediate height on the inside of the meander curves. The re-worked earlier gravel deposits, perhaps augmented by the contribution of a quota of pebbles transported directly from Pennsylvanian conglomerates by such tributaries as Obey River, have furnished pebbles in sufficient amounts to sprinkle the alluvium. This stage of alluviation came after two-thirds or three-fourths of the total down-cutting was accomplished. Further study will be necessary to determine its relation to other geologic or physiographic events.

Hayes and Ulrich refer to deposits of coarse gravel on the western Highland Rim Plateau in the Columbia quadrangle, Tennessee, and state that the pebbles are thoroughly water-worn, and composed in part of chert and in part of vein quartz. They find it difficult to explain the origin of the pebbles of vein quartz, but believe that the deposits may have been formed by streams upon their flood-plains when the physiographic surface now represented by the Highland Rim Plateau was nearing completion.[2]

Galloway describes a deposit of gravel in Rutherford County, tentatively assigning it to the Pliocene period. The position of this bed at an altitude of 580–700 feet is intermediate between the Highland Rim and the present topography. Galloway states also that there are similar deposits at corresponding elevations along Cumberland River.[3] He does not give the basis for his dating of the deposits, and his reference to the deposits along Cumberland River does not place the locality so that even a tentative correlation may be made with the stage discussed in the Gainesboro-Thompkinsville area.

[1] Bruce Wade, "Recent Studies of the Upper Cretaceous of Tennessee," *Tenn. Geol. Survey Bull. 23* (1920), p. 54.

Hugh D. Miser, "Mineral Resources of the Waynesboro Quadrangle, Tennessee," *Tenn. Geol. Survey Bull. 26* (1921), p. 25.

[2] C. Willard Hayes, and Edward O. Ulrich, *U.S. Geol. Survey Geol. Atlas, Columbia Folio, No. 95* (1903), p. 1.

[3] J. J. Galloway, "Geology and Natural Resources of Rutherford County, Tennessee," *Tenn. Geol. Survey Bull. 22* (1919), pp. 17–22.

NOTE ON THE ANGLE OF FRACTURE CLEAVAGE

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ABSTRACT

Fracture cleavage was developed in connection with a fault in massive limestone. The cleavage made nearly the same angle with the vertical that the fault made with the horizontal. Otherwise, the cleavage fractures appeared to have the general character of repeated faults.

GENERAL PRINCIPLES

Theoretically there is a genetic connection between thrust faulting, jointing, and fracture cleavage. Frequently all three have been assumed to occur in the planes of maximum tangential stress in rocks. Stresses in rocks are referred to three principal axes at right angles to each other. One of these is the greatest axis of stress; another, the least axis; and the third is an intermediate axis of stress. In non-rotational strain the planes of maximum tangential stress are parallel to the intermediate axis and make an angle of 45° with the greatest and least axes. Thus there are two sets of these planes, dipping in opposite directions, and they intersect along lines parallel to the intermediate axis and at right angles to the greatest and least axes. Breaking takes place along these planes under simple laboratory conditions, and sometimes it has been assumed that thrust faults should occur in these 45° planes. Actually, however, the angle that thrust faults make with the greatest axis is reduced by friction,[1] the amount of reduction depending on the coefficient of friction of the material. Therefore, theoretically, under ideal conditions, faults due to compression should occur in two planes, dipping in opposite directions, with the greatest axis of stress bisecting the acute angle between the planes. Under simple conditions faults conform to this rule. Joint planes and fracture cleavage are, however, more complex.

[1] B. Stevens, "The Laws of Fissures," *Trans. Amer. Inst. Min. Eng.*, Vol. XL (1909), pp. 475–91; R. T. Chamberlin and W. Z. Miller, "Low-Angle Faulting," *Jour. of Geol.*, Vol. XXVI (1918), pp. 14–19.

THE SPECIFIC PROBLEM

Fracture cleavage and jointing were formed in connection with a fault that has been exposed by excavation in a cement rock quarry at Portland Point on Cayuga Lake, New York. This cleavage and these particular joints were evidently secondary to the faulting. An opportunity has thus been given to compare the theoretical stress relationships with good field examples, as all three types of fractures were formed under the same regional stresses and the positions of the axes of stress are known.

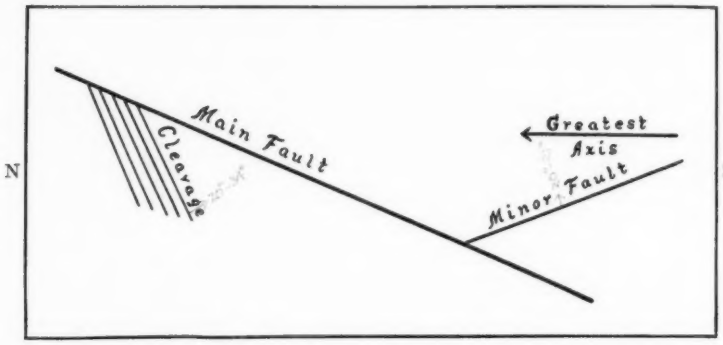

FIG. 1.—Cross-section diagram showing the angles made by the fracture cleavage and faults with the greatest axis of stress.

Figure 1 shows the angles of the faults and cleavage. There was one main fault which probably passed entirely through a layer of massive limestone about 20 feet thick. Minor faults, associated with the main fault, dipped in the opposite direction and had nearly the same angle of dip as the main fault, making the faults symmetrical about a nearly horizontal plane. Readings on the main fault gave the angle of dip as 22°–25° S., and on the minor faults as 20°–21° N. The strike of the faults was nearly E.W., or roughly parallel to the axes of the low folds of this district. It is evident that the greatest axis of stress lay in a nearly N.S. line and in a nearly horizontal plane. The faults fulfilled the conditions expected from the stress theory of breaking planes. They formed two sets which were symmetrical about the greatest axis (horizontal) and intersected along

the intermediate axis (E.W). As the rock was competent, the greatest axis bisected the acute angle between the faults.

This position for the greatest axis of stress is supported by other evidence in this vicinity. As the low folds presumably were formed during the Appalachian revolution, the active force can be described as horizontal compression directed from the south in this area. In this district small faults that are symmetrical about a nearly horizontal plane are characteristic of certain calcareous layers lying between weak shales. They resemble breaks obtained in faulting experiments when several strong layers alternated with much weaker ones.[1] The faults are common in the encrinal (Tichenor) limestone near this quarry.[2] Similar faults have been found in a calcareous layer only three inches in thickness about ten miles south of this quarry. It is evident that the presence of thick shales above and below the competent layers permitted the faults to move with almost equal freedom along either of the two theoretical breaking planes. The orientation of the greatest axis does not vary widely in this district, so that the regional forces acting at the time this fracture cleavage was formed are rather definitely fixed.

At various points along the main fault at the quarry, fracture cleavage was formed, as shown in Figure 1. In places these fractures were very evenly developed, with several plates to the inch. The surfaces were polished, but not striated like slickensides. They had the appearance of closely set, repeated faults. This similarity was strengthened by the fact that their strike was nearly parallel to the strike of the faults. In dip, however, they were widely different from the faults. The hade of those measured varied from 20° S. to 34° S.; that is, they made nearly the same angle with the vertical that the faults made with the horizontal. In a group of cleavage fractures one fracture had a hade of 21° N. This probably indicates the same tendency toward symmetry shown by the faults, but, in the case of the faults the acute angle faced the horizontal axis, while in the case of the cleavage the obtuse angle faced the horizontal axis. The angle of hade of the cleavage fractures varied notice-

[1] R. T. Chamberlin and W. Z. Miller, "Low-Angle Faulting," *Jour. of Geol.*, Vol. XXVI (1918), p. 26.

[2] *Jour. of Geol.*, Vol. XX (1912), pp. 60–62, Fig. 3.

ably, and there was some indication that it varied with the distance from the fault line. This variation may have been analogous to the change in direction of cracks produced in joint-plane experiments.[1]

There seem to be several possible explanations for the angle of the fracture cleavage. One is to apply the strain theory to the cleavage. According to this theory the greatest axis of stress would bisect the obtuse angle between the planes, not the acute angle. In a recent paper C. O. Swanson[2] applied the strain theory to fracture cleavage in incompetent rocks. In its usual relationships the Tully limestone is not an incompetent rock. At the fault line, however, the limestone was broken and crushed until it formed breccia or even gouge. This crushed zone was one or two feet in thickness. The fracture cleavage did not extend more than three or four feet below the fault, and it is possible that the rock was so weakened by crushing before the cleavage was formed that it acted as an incompetent rock.

Another possibility is that during the readjustments incidental to the shifting of the rock masses during faulting, the vertical axis became greatest and the N.S. axis became least at some points along the fault. With such a redistribution of the effective stresses the breaks might form with the same strike as the main faults and at an angle with the vertical equal to the angle that the main faults made with the horizontal.

A third possibility is suggested by the angle between the fault and cleavage fractures, which was about 45°. The position of the cleavage may have been determined by the angle with the fault rather than by the angle with the main stress axes, suggesting that the cleavage developed after the inception of the faulting in consequence of altered stress conditions in the foot-wall due to slip on the fault plane.

In general, these cleavage fractures suggest that they were formed according to the laws of breaking for faults, but under such conditions that the applied force was evenly distributed, thus causing a series of breaks rather than a few master-breaks, like faults.

[1] *Jour. of Geol.*, Vol. XX (1912), p. 168. Fig. 11.

[2] C. O. Swanson, "Notes on Stress, Strain, and Joints," *Jour. of Geol.*, Vol. XXXV (1927), pp. 193–223.

As joints are related to faults, it is noteworthy that certain joints formed in association with these faults and cleavage fractures were very different from either. They were dip joints. They were nearly vertical, and were oriented nearly at right angles to the strike of the faults and cleavage fractures. In Figure 1 they were parallel to the plane of the paper. These transverse joints occurred in a band just above the brecciated fault zone. All of the cleavage fractures observed were below the fault line.

SAND HOLES OF THE STRAND

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ABSTRACT

The numerous small sand holes occurring along the strand-line are not mollusk or crustacean burrows, but are air vents from shallow channels formed in stratified beach material by the action of waves passing over the strand.

One of the many features of that spawning-ground of geological phenomena, the sea beach, is the numerous small holes that occur along the strand line. As seen on the surface they appear to be vertical, are irregularly spaced, and are sometimes so numerous that their numbers are comparable to the perforations of a saltshaker (Fig. 1). Their diameters vary from less than a millimeter to 6 millimeters. They are confined to sandy beaches and to that part of the strand within the reach of the waves. They are more frequent where the coast is buffeted by swells, and, as far as personal observation bears witness, most numerous in the vicinity of the mouths of small streams that contribute a variety of beach material. This type of beach material readily lends itself to stratification when subjected to the milling action of waves (Fig. 2).

These holes are noticeably absent along muddy shores and very infrequently where the beach is of homogeneous sand and the stratification as a result imperfect.

These holes have been attributed to burrowing mollusks and to shrimps. On general grounds this explanation is hardly plausible, as the holes along the Washington coast are entirely similar to those on the coast of Oaxaca, Southern Mexico, 2,200 miles to the south and in a widely separated faunal province. Not a single mollusk common to the two named coasts was observed, though burrows entirely similar would suggest identity in the species of burrowers. Furthermore, sandy wave-swept beaches are for the most part barren of molluscan life, owing to the shifting of the sands, which is

fatal to burrowing bivalves. The variation in the sizes of the holes and their local profusion, together with the almost total failure to

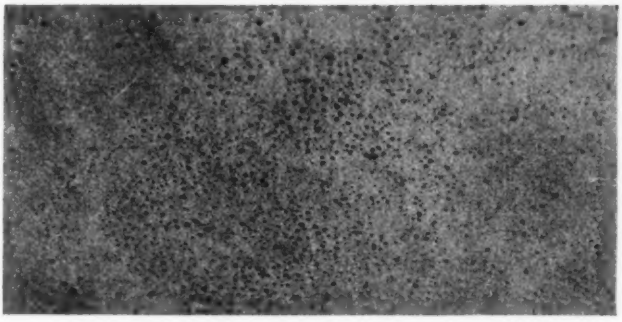

FIG. 1.—Sand holes

FIG. 2.—Section of strand through a group of sand holes. Note small cavern and arch in the fine-grained bed.

encounter mollusks or shrimps at probable depths, seem to preclude burrows as an explanation.

If the beach be sectioned through a group of these holes, it will

be observed that it is made up of a series of thin alternating beds of coarse and of fine sand, and that the holes occur in the upper 10 or 15 centimeters, though traces 30 centimeters deep are occasionally encountered. The holes are not vertical except where they perforate the surface; rather, they follow beds of coarse sand down the initial dip a few centimeters and then penetrate the finer-grained beds below to the next coarser one, which they in turn follow. A single channel may repeat this several times, the final result being that the hole descends by a series of steps that advance down the initial dip of the sand beds toward the water.

The following interpretation seems in harmony with these observed data. A wave passing over the strand saturates the sand below. As it recedes the pressure on the ocean side decreases and most of the water within the sand drains laterally down the beds that have an initial dip toward the ocean. A relatively small amount sinks vertically across the bedding planes. The draining off of the water and the consequent replacement by air is more rapid within the beds of coarser grains than in those of finer grains. This produces alternating beds of saturated and of unsaturated sand. With the next wave the surface is again covered and the pressure from the increased column upon the sand under the advancing wave forces the water back up the dip of the coarse-grained beds. Observation indicates that there is a lag of several feet in the movement of this subsurface water behind the vanguard of the wave. The wave effectively seals the surface and entraps the air in the coarser-grained beds below. The accumulating column under the advancing wave exerts sufficient pressure on the confined air to force it through the less porous thin beds into the overlying more pervious ones, and thence up the dip and by one or more repetitions finally to the surface. During this process the fine beds are bent upward, and it often happens that the sand wedges in the form of a dome, thus preserving a small cavity (Fig. 2). If the action is observed with care, air bubbles carrying sand are seen to burst through the film of water in the farthest reaches of the wave as it starts to recede. Later, in the withdrawal of the wave and the subsequent draining of the more porous beds, air is drawn into these beds through the holes. Succes-

sive waves during a given stage of the tide further develop these holes and their channels below by somewhat extending them and by clearing them of sand.

During flood tide the incipient stages of this phenomenon may be witnessed. The pressure behind the air often is not sufficient to force it through to the surface, but merely suffices to arch the surface layers of the sand into small flat domes a quarter of an inch high and two or three inches in diameter (Fig. 3). These are ex-

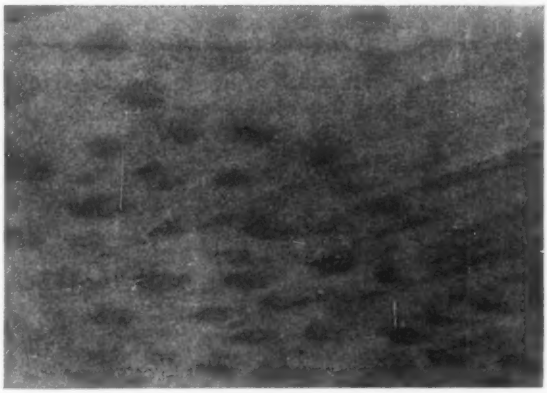

FIG. 3.—Small mounds, the incipient stages of sand holes

tremely fragile and collapse from the jar of footfalls. The domes are soon ruptured by subsequent air blasts from the channels below. The little mounds often resemble miniature volcanoes when they burst and eject the sand grains caught in the rush of air. The material of the domes is soon removed by successive waves, leaving the holes in question.

This interpretation is merely a statement of the dynamics involved in their production. The phenomena producing the channels and their vents are fleeting, and observations must be made literally between waves.

The numerous small shrimps that feed along the strand line take advantage of these holes and use them and the subterranean pas-

sages as ready-made burrows. Not only are they occasionally seen entering them, but they are often found underground. This very probably gave rise to these holes being interpreted as burrows.

These holes are of interest to the paleontologist, as they are frequently found in "fossil" form. In my own collection there are a number of small irregular cylinders that were labeled "worm-tubes?" under the impression that they were worm burrows that had been filled and preserved. It is very probable that these tubes are air chambers formed as described and their form preserved. These are analogous to the "clam necks" that are so commonly encountered in the Tertiary. The so-called "necks" are in reality the vertical channels made by several groups of burrowing clams, of which the *Mactridae* is the best example. Through it the animal thrusts the siphon or "neck" up to water above. The hole is kept open by a lining of mucous material. When the animal dies the hole is filled with fine débris, and under favorable conditions the form persists and is subsequently indurated along with the muddy matrix. In the case of such channels the failure of the mucous lining renders the chance of their preservation much more precarious.

REVIEWS

Isostasy. By WILLIAM BOWIE. New York: E. P. Dutton & Co. 1927. Pp. 275; figs. 39. $5.00.

In this very readable book Dr. Bowie has given a clear statement of the isostatic theory and its geological bearings. As the literature of isostasy has now reached bulky proportions, such an authoritative and comprehensive yet simple treatment of the subject in one volume will be welcomed by students of earth dynamics. The development of the isostatic theory, the quantitative tests and the underlying assumptions comprise the first three chapters. Isostatic conditions and deductions, phases of adjustment, geological deductions, and processes involved carry one to the final chapter, which presents the theory proposed by the author to account for major changes in the elevation of the earth's surface. The subjects are well handled and give the reader an excellent understanding of isostasy together with its significance and applications, as interpreted by Dr. Bowie.

On the other side of the picture, the reviewer wishes to touch briefly upon a few points. It is stated by the author and very commonly taken as a fundamental assumption that the rigidity and strength of the earth-shell decrease "from the surface down to some depth below sea-level, where a change in condition occurs. Below this materials may be rigid in the sense that they do not yield under stresses acting for only short periods of time, but they yield and conform to stresses, comparatively small ones, acting for long times, such as hundreds or thousands of years" (pp. 18–19). This time dodge, much used lately in various quarters, in reality applies not only to rocks deep beneath the surface, but also to rocks at the surface, or even above the surface of the earth. Tombstones and slabs covering old structures sag and bend under their own weight in the course of time. Conspicuous weakness and notable plasticity approaching liquid behavior are, however, not implied by the bending of the tombstone, nor should these properties be attributed to subsurface rocks in the earth. They cannot legitimately be used as an oxygen stimulant to revive the venerable Hadean conception of liquidity or near-liquidity beneath a thin surface crust of the earth. The insidiousness of the argument lies in the fact that the isostasists apply the principle of slow yield (which takes place by idiomolecular transfer in true solid fashion) not to all rocks, as

they should, but limit it, by implication at least, to their chosen zone beneath the rigid rocks within sight. Quasi-liquidity is no more indicated by the principle of slow yield through idiomolecular exchange at a depth of sixty miles than it is at the surface.

Quite contrary to this assumption of decreasing strength with depth, the experiments of F. D. Adams, Bridgman, and others, upon rocks under high compression, lead definitely to the conclusion that with increasing depth below the surface, greater and greater differential stresses are required to cause yielding. In the outer part of the earth, at least, the rocks increase in strength with increasing depth. Much more investigation along these lines is needed to determine how far this increase is actually extended. Pending a thorough analysis of the effects of increasing balanced pressures and increasing temperature within the outermost hundred or couple of hundred miles of the earth, the conclusions which the isostasists constantly claim as "proved" must, in the opinion of the reviewer, be taken with much reserve. The isostatic simile of blocks of wood and ice resting in water (p. 19) and the induced rigidity of actual experimentation do not jibe.

It is the habit of the advocates of isostasy to compare the average gravity anomaly, derived from calculations based on their assumptions, with "what it would be on the rigid-earth hypothesis" (pp. 47–48). If by "rigid-earth hypothesis" they have in mind an unyielding earth, they are introducing an imaginary criterion. Complete rigidity has no place in science. In diastrophism the earth material yields beyond any question and the great amount of folding and thrust faulting, often with extensive cleavage and schistosity, indicates vastly more crustal shortening under horizontal compressive stresses than the isostasists have ever been able to explain. The true test comparison lies between hydrostatic balancing and yield and balancing and yield by elastic stress-strain, the most common mode of balance and yield of outstanding bodies on the surface of the earth, both natural and artificial.

As brought out in this work, a high mountain block undergoing erosion would, on the isostatic principle, rise steadily in proportion as its upper portion is being removed. The rise would continue until heavier material from adjoining areas coming in below the mountain column, combined with contraction of the column due to cooling and its derivatives, eventually equalizes the density sufficiently to stop the upward movement. Before this can take place and peneplanation result, a stupendous quantity of rock, much more than field evidence will allow, needs to be removed from the upper part of the mountain column. Peneplana-

tion, a widely prevalent geologic process, seems to be in direct conflict with the standard isostatic conception. Peneplanation indicates still-standing conditions for long periods of time.

To the geologist perhaps the greatest shortcoming of the theory presented in this book is the treatment of mountain folding. There is little appreciation either of the extent of folding and thrust faulting or of the necessity for some mechanism which gives strong horizontal compression. The assigned mechanism, in the opinion of the reviewer, could give only relatively feeble horizontal compression of a very different order of magnitude from that required by the field facts. Vertical adjustments between shallow blocks are not a source of great horizontal squeeze. On page 178 is the statement: "Parallel ridges cannot be the result of regionally acting forces; therefore, they must be due to local forces." Yet the American Cordilleras are formed of parallel ridges and flank the Pacific borders of both American continents from Bering Strait to Cape Horn and are continued along the west border of Antarctica as well as in northeastern Asia at the other end—altogether fully one-third of the circumference of the globe. The subject of mountain building calls for the world-map.

Geodesist and geologist meet on common ground in the statement (p. 18): "Much has been claimed for isostasy as an active agent, but it is a condition of rest." Whatever the truth in regard to isostasy may be, it is clearly secondary to the geologic processes in operation. But here the divergence of views begins. According to Bowie, the primary causes of the major changes of the earth's surface are evaporation, precipitation, erosion, and sedimentation (p. 267). Light material is transferred by surface processes from the postulated light columns to the surfaces of the depressed heavy columns and, to compensate, heavy material is transferred by deep-seated movement from the bottoms of the heavy columns to the bottoms of the light columns, thus gradually equalizing the densities of the columns. These processes have thus been in operation throughout geologically recorded history to bring the surface of the globe toward a common level. The surface relief of the lithosphere on this view is steadily diminishing. The relief features of the Paleozoic should have been less pronounced than those of the Proterozoic, those of the Mesozoic less than those of the Paleozoic, and today we should witness an earth surface still further reduced in topographic relief. The mechanism of necessity runs steadily down, for it works toward eventual equilibrium and a crust of uniform density. On a molten-globe hypothesis, whatever started such great surface relief, since, in a liquid state, a high condition of equilib-

rium and relatively homogeneous material, horizontally, is naturally to be expected?

According to other views, growth and diastrophism are the most fundamental of the processes producing the major relief features of the earth. Erosion and a long chain of events follow. The episodes of diastrophism are the positive beats of the geologic rhythm. In the folding of geosynclinal tracts into mountains the weaker rocks are folded and uplifted. The weak sediments are also light, which is favorable to uplift. In diastrophic movements the densities of the rock material are all in the equation of forces and resistances, and it is natural enough that, in general, the material in uplifted tracts should have lesser density than that beneath the depressed areas. Furthermore, in the middle portions of intensely folded belts many intrusions of light granitic rocks are a characteristic feature. They may represent the lighter differentiates of heavier magmas below, the differentiation and rise toward the surface being interrelated phenomena. Because of their closeness to the geodetic instruments on the surface, they exert, on the principle of inverse squares of the distances, a preponderating influence on gravity determinations. Large or numerous batholiths high up in a mountain block may thus make the determined value of "g" less after the intrusion than it was before, even though the total weight of the chosen rock column down to sixty miles should remain the same. Katamorphism of the exposed rocks in a mountainous region may also reduce the specific gravity of the high-standing masses.

Over large areas of the globe there is but little surface relief to be compensated; hence, the most favorable tests of the isostatic theory are in the areas of greater relief where diastrophism has been most active. In such areas, as just noted, other processes and factors, not taken into account in the isostatic conception, may be of prime importance in giving the computed results upon which the isostasists base their present theory. The assigned explanations of the geodetic results and their interpretations in terms of earth processes are, therefore, very unconvincing to many geologists.

Dr. Bowie has done a very useful piece of work in bringing forth such a concise statement of the development of the isostatic theory, its general nature, and geological applications and implications, as viewed at present by the chief investigators in the isostatic line. The book is remarkably easy to read for one treating such fundamental and complicated topics.

R. T. C.

Vulkankunde. By KARL SAPPER. Stuttgart, 1927. Pp. 424, maps 4, pls. 30, and numerous text figures.

Doubtless it was with the definite intention of indicating the somewhat restricted scope of his work that Professor Sapper has used the term *Vulkankunde* as descriptive of his treatise, rather than *Vulkanismus* or *Vulkanologie.* Essentially it is a book on the activity of volcanoes, rather than on volcanology, and decidedly not a book on igneous rocks or magmas. He explains in the Preface that what he had chiefly in mind was to awaken in the reader the clearest possible conception of volcanic processes. Therefore, one should not expect elaborate discussions of the constitution of the earth's interior, the fundamental causes of volcanic activity, phenomena of igneous intrusion, the relation of volcanism to tectonics or orogenesis, or the chemistry of the magma and the processes of magmatic differentiation. Such discussion as is given to these subjects is chiefly to establish a background for the main theme.

Plainly, a volcano in action is for Sapper a subject of fascinating interest, and what came before the eruption or follows after is of much less concern. If there has been no record of activity the volcano receives little or no attention. For example, we find no mention in the Index and apparently none in the text of the great peak Sajama in Chile or of the giant crater Ngorongoro in East Africa. Even Kenia and Kilimanjaro are omitted; likewise Knife Peak, the highest of the Katmai group.

In places his lack of interest in other phases of investigation leads to statements hardly warranted, as where (on p. 67) he dismisses the researches of earth-physicists with the statement that they are able to give no reliable information upon the building-up of the earth's crust or upon the processes of uprise of magma. This attitude, however, is somewhat modified in other parts of the book, and especially in the last chapter, which gives an excellent summary of the historical development of volcanological science from ancient times to the present; here the contributions made by physicists and chemists are by no means slighted.

The first chapter, written before the war by the late Dr. Bergeat, and intended as a petrographic introduction, is hardly an adequate presentation of our later knowledge, and one feels that Dr. Bergeat himself, if living, might wish to change it. Laboratory investigations of the last fifteen years are not touched upon.

These features do not, however, detract greatly from the general excellence of treatment in Sapper's special field, which forms the main body of the book. An outstanding feature is the impartial presentation of data. In some of the books on igneous rocks that have appeared in recent years

the authors have adopted certain favorite theories on matters which, impartially regarded, should be considered as still under judgment, and manifest a tendency to interpret phenomena in accordance. Nothing of the kind is apparent here. The sole object seems to be to present the available information as clearly as possible, and it is plain that he has taken great pains to learn exactly the meaning that the author has desired to convey. For this, authors who, in other works, have found their cherished theories mauled out of recognition by careless abstractors should be very grateful.

Where, on important problems, conflicting views have been expressed, Sapper is careful to give all the parties to the controversy their day in court; in fact, possibly a little too much leniency is shown toward views which are hardly tenable, but no harm is done in leaving partly to the reader the exercise of critical faculties.

Special prominence is given to those researches of recent years in which the investigators have endeavored to go beyond visible manifestations and inquire into hidden causes. We may mention, for example, Sapper's careful and thorough presentation of the work done on Kilauea, Mount Lassen, the Katmai region, and Montagne Pelée; the citation of analyses of volcanic gases and sublimates; and the descriptions of glowing clouds.

It is an impressive picture of the multifarious activities of volcanoes that Sapper lays before us. One feels that he has not only come very close to his avowed object of presenting "the expressions of activity of every single volcano," but that he has done much more than this in relating them in time and space, and correlating them with other physical features of the globe. He has covered an important field of which only parts have previously been covered, and which no English or American author has approached, and he has done it exceedingly well.

The book is written in not difficult German, with few involved sentences. The printing is well done, on a soft paper of matt surface. Most of the photographic illustrations, on a paper of special surface, are of excellent quality.

C. N. F.

The Earth and Its Rhythms. By CHARLES SCHUCHERT and CLARA M. LE VENE. New York: D. Appleton & Co., October, 1927. $4.00. Pp. 410; figures, 173.

The book is a popular reader intended to give the layman an insight into geologic processes and the results which they have accomplished.

The last two-fifths of the book are devoted to an outline of earth history presented parallel with a general account of the ways in which the geologic record is read. The authors' point of view is well summed up in the following extract from the Preface: "But fortified by the belief that the story of the rocks and the life record within them should be a part of our common intellectual heritage, we hope, by the process of filtering a great mass of geologic detail through a non-scientific mind, to have obtained a residue that will be sufficiently free of technicalities to be comprehensible to the layman." The reviewer has tested the book by giving it an oral reading in a non-scientific circle and he believes it to accomplish the purpose which the authors have expressed the desire it should accomplish.

Two very excellent features are the remarkably clear, concise, and non-technical statement of the principles of organic evolution and its geologic and paleontologic evidences, and the fact that less than a dozen of the drawings and photographs are from non-American localities.

Altogether the book is one with which the geologist can meet the frequent inquiries for a general, cultural reader.

F. A. BURT

The Physiography of the Region of Chicago. By F. M. FRYXELL. University of Chicago Press, 1927. Pp. 55; figs. 17, pls. IV. Map in pocket. Price $2.50.

The application of geology to the furtherance of human welfare takes many diverse forms, but none more interesting or more novel than that which is exemplified in the *The Physiography of the Region of Chicago.* This is one of those significant regional studies, all too rare as yet, which place at the disposal of a great community all the essential geologic and physiographic data which are needed in planning the city of the future. Sponsored by the Chicago Regional Planning Association, it was written with the definite purpose of providing a solid foundation of fact upon which to build the plans for the greater Chicago that is gradually taking shape, a city to be based upon intelligent utilization of every natural feature.

The area covered by this report extends north of Chicago along the Lake Michigan shore beyond Racine, west beyond Elgin and Aurora, south to Kankakee, and east to LaPorte, and includes an area of some 7,000 square miles. Including, as it does, the land within a radius of fifty miles from Chicago, it covers not only the present suburban district, but also an outer zone of great importance to the city for recreational and

residential development. By applying such a study as this, which focuses attention on the potential utilization of the outer zone, Chicago may avoid many of the mistakes which result from lack of concerted, far-sighted planning.

The subject matter of the book includes, not only the strictly physiographic description of the area, but also a direct, clean-cut application of physiographic data to questions of community planning. Thus some of the chapter headings are: "The Lake Plain, a Great Industrial Area"; "The Lake Border Upland, a Residential and Recreational Area"; "Lake Michigan and Its Shore Line"; "The Bed Rock and Its Surface, a Buried Landscape"; "The Surface Materials, Basis of Our Agricultural Wealth." While such titles very properly imply a considerable emphasis on human geography, the basic facts of geologic and physiographic history are clearly stated and illustrated with admirable diagrams.

The illustrative material of the book deserves a paragraph to itself. The reviewer is inclined to believe that the four large colored maps, which are conveniently folded in with the text, represent a new high-water mark in American map printing. For harmony of color and for complete legibility they compare favorably with the finest British and German maps which have been the open envy of American map users for years. There is a large detailed base map of the Chicago region in a pocket, showing all political boundaries, land subdivision lines, highways, railroads, canals, with names in each case, and a five-minute latitude and longitude grid. In addition to these five plates, there are thirty-three figures, including maps, profiles, block diagrams, cross-sections, and photographs.

Lest the reader begin to suspect that this review is a mere indiscriminate song of praise, some of the less satisfactory features of the work may be mentioned. The convenience of the four colored maps is reduced by the absence of any indication of their scale. The stiff paper covers are by no means all that could be desired, and the margins are too narrow to permit satisfactory rebinding. The large page size (quarto) is unusual in books dealing with similar subjects, but seems to be justified by the greater convenience of using maps with fewer folds. The double-column arrangement of the text is not particularly pleasing, especially when seen in conjunction with the narrow margins. A single column with wider margins would require some additional pages, but the resulting book would seem to be more acceptable from the mechanical point of view.

The reviewer cannot refrain from commenting on the high literary quality of the book. Rarely are trained scientists blessed with a com-

bination of time, inclination, and aptitude to produce a work of such satisfying literary finish as we find here, coupled with such painstaking accuracy.

J. R. V. P., Jr.

Voordrachten over de geologie van Nederlandsch-Oost-Indie. (*Lectures on the Geology of the Netherlands East Indies.*) By L. M. R. Rutten. 8vo., 16×25 cm. Pp. x+839 with numerous sketch maps and illustrations. Groningen: J. B. Wolters, 1927.

This voluminous treatise by the professor of geology in the University of Utrecht (Holland) is a welcome complement to Brouwer's earlier American lectures on the same subject, which were recently noticed in this journal. While Brouwer's book may be termed an outline of the major features, particularly of the tectonic features, this work is essentially a descriptive geology of practically all of the separate islands of the Malay Archipelago. With amazing industry the author has brought together and critically sifted the information from numerous and varied sources, including his own observations and investigations. The result is a valuable source book of fundamental importance, which is bound to unify and stimulate further geological research in that part of the world.

The book contains forty-nine chapters, originally lectures, of which five have been devoted to Java, nine to Borneo, eight to Sumatra, two to the tin islands, etc. They are accompanied by numerous sketch maps and illustrations of the type fossils, which should prove a great help to the foreign student who is likely to find difficulty in deciphering the Dutch text.

The author's field of specialization may be inferred from the greater emphasis that has been placed on stratigraphy and historical geology. In this connection it is interesting to realize that the present aspect of this vast area, as large as the United States of America, is but of recent origin, the Tertiary and Quaternary periods having been responsible for most of it. The Tertiary was characterized by widespread and progressive sedimentation with little change of facies, in places, to an estimated thickness of 33,000 feet. It was followed by a period of greatest mountain-building and volcanism, at the end of Tertiary time, which processes have given rise to mountain ranges and volcanic peaks as high as 15,000 feet. These orogenic movements are active to this day in many parts of the Archipelago.

Economic geology, in this book, has not been neglected, as may be

gathered from the two chapters on the tin islands, from separate chapters devoted to the useful minerals of the larger islands, and from a chapter on petroleum, all of which make the work a well-balanced summary of what is (officially!) known to date concerning the geology of the Malay Archipelago.

If someone else of the author's countrymen will now produce a similarly systematic treatment of the physiography of this region, the Dutch may take pride in having completed the first comprehensive physical survey of such a large area in the tropics.

M. W. S.

Tabellen zur allgemeinen und speziellen Mineralogie. By PAUL NIGGLI. Berlin: Verlag von Gebrüder Borntraeger, 1927. Pp. xvi+300; 228 figs. Cloth, M. 9.30.

This work, divided into six parts, presents tables to be used primarily for mineral determination purposes. Excepting blowpipe and X-ray characteristics, essentially all fields are covered, although the crystal-determination tables are based on habit rather than angles.

From the point of view of the American student, Part II is of most interest, as it combines a small crystal atlas into tables for determination by crystal habit, luster, and cleavage. Such a table in English is unknown to the reviewer, and is an innovation of considerable potential value. This table also gives physical properties and geologic associations and occurrences. Part III may be considered as a key to Part II based on color and hardness.

Parts I and VI include graphical summaries of certain features of geometrical crystallography and of optical crystallography, the latter preceding optical determination tables. Other parts include tables emphasizing some particular feature (streak, specific gravity, structure, or geologic occurrence) as well as tables listing minerals by elements and by uses, the precious stones receiving particular treatment.

D. J. F.

Lehrbuch der Geophysik. No. 1. By Various Authors with Preface by B. GUTENBERG. Berlin: Gebrüder Borntraeger, 1926. Pp. 176, figs. 52, tables 37. M. 9.75.

This is the first portion of a general treatise on geophysics written by several authors under the editorship of Dr. Gutenberg. The major divisions are as follows: "The Development of the Earth and Its Geological Construction," by A. Born; "Gravity and Isostasy," by E. A. Ansel;

"The Mechanics of Movement of the Earth Crust," by A. Born; "Water, Ice, and Wind as Major Geologic Agents," by A. Born; "Vulcanism," by A. Born; and "Earthquake Geology," by A. Sieberg. Owing to the wide range of topics, the discussion of each is quite brief, but the treatise is valuable as a convenient source of information, and for concise discussions of various theories and opinions upon many fundamental questions of geology.

R. T. C.

Productidae of China. Part I, *Producti*. By Y. T. CHAO. Geological Survey of China, *Paleontologia Sinica*, Series B, Vol. 5, Fascicle 2. Peking, 1927. Pp. 192; pls. 16; text figs. 7.

Chao's monograph presents a new classification of the genus *Productus*, the genus being divided into thirteen subgenera, five of which are new. The classification is based upon the shape of the living chamber, the ornamentation of the shell, and the interior structures. Twenty new species are described. The specimens studied are from Carboniferous and Permian rocks of localities in all parts of China. The plates are many and good; several figures of each species are given. Chao was directed in his studies by A. W. Grabau.

C. C. B.

Queen Anne's County, Kent County, Talbot County. Maryland Geological Survey. Baltimore: Johns Hopkins Press, 1926. Three vols. Pp. 175, 177, and 184; maps.

Each county report has a chapter on each of the following subjects: physical features, previous work and bibliography, physiography, geology, mineral resources, soils, climate, hydrography, magnetic declination, and forests. The volumes are excellent references for the areas they cover. They contain good illustrations and give plates of the index fossils of the formations represented in the counties. Large-scale areal geologic maps of the formations, soil maps, and forest maps accompany the reports.

C. C. B.

Transactions and Proceedings of the New Zealand Institute, Vol. 56 (New Issue). Wellington: Government Printing Office, 1926.

Besides numerous papers of local geological interest, this volume contains the following works:

P. Marshall, "The Upper Cretaceous Ammonites of New Zealand," pp. 129–210. Plates, 28.

H. J. Finlay, "New Shells from New Zealand Tertiary Beds. Part 2," pp. 227–58. Plates, 6.

J. Marwick, "Tertiary and Recent Volutidae of New Zealand," pp. 259–303. Figs., 86.

Further papers describe many new species of mollusks from the Jurassic and from the Tertiary.

C. C. B.

The Cretaceous and Tertiary Foraminifera of New Zealand, with an Appendix on the Ostracoda. By FREDERICK CHAPMAN. Wellington: New Zealand Department of Mines, Geological Survey Branch, *Paleontological Bulletin No. 11* (1926). Pp. 119; plates, 22.

The Bulletin describes 277 species of Foraminifera and twenty-eight species of ostracods. Sixteen species are new. All species are figured and the plates of previous papers on the subject are reproduced, making this paper a complete reference volume for New Zealand. Ninety per cent of the Foraminifera are Cenozoic, the rest Cretaceous; all but one of the ostracods are Cenozoic.

C. C. B.

Geology and Natural Resources of Colorado. By R. D. GEORGE. University of Colorado, Boulder, 1927. Pp. 228; illustrated; 67 figs. Price, $2.00.

This book is, in a sense, a textbook of geology which takes its examples of geologic phenomena and its illustrations from areas in Colorado. The writer discusses petrology, historical geology, stratigraphy, and economic geology in a general way, and then takes up these subjects as they apply to Colorado. The ore deposits, coal beds, and petroleum areas are discussed by districts in an organized manner. To stratigraphers, the four stratigraphic sections which are given will prove valuable. A small geologic map of Colorado is included. Chapters on water resources, soils, forests, national parks, fish and game, and climate and scenery close the book.

George writes in a fluent and well-arranged manner, and to any geologist *Geology and Natural Resources of Colorado* will make interesting reading.

C. C. B.